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CORRELATION OF OIL SANDS BY SEDIMENTARY ANALYSIS.

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INTRODUCTION.

THE investigation described in this paper was designed to discover if producing oil sands can be recognized and correlated by their physical characters. In many sands there are no fossils by which they can be recognized and in others the micro-faunas are so meager as to make identification impossible. The work demonstrates the practicability of physical correlation where micro-faunas fail and its value as a check on paleontologic determinations.

For purposes of correlation by sedimentary analysis, four producing sands in northeastern Oklahoma, the Wilcox, Hominy, Bartlesville and Elgin sands, were chosen. Fifteen samples from each of the four sands distributed as shown in Fig. 1 were secured from Mr. Luther White of the Hull Oil Company, Mr. R. F. Baker and Mr. A. E. Stander of the Texas Company, Mr. Fritz Auren and Mr. Glen C. Clark of the Marland Refining Company, and Mr. Leo G. Keppler of the Southwestern Oil Company, and analyzed in the laboratory. All were subsurface samples from well cuttings except seven collected from surface exposures of the Elgin sand. Although most of the samples came from the collectors designated as belonging with one or another of these four sands, a few, among which are H–13, H–15, and B–16,

were not certainly located stratigraphically when collected and have been correlated by their physical and faunal characters.

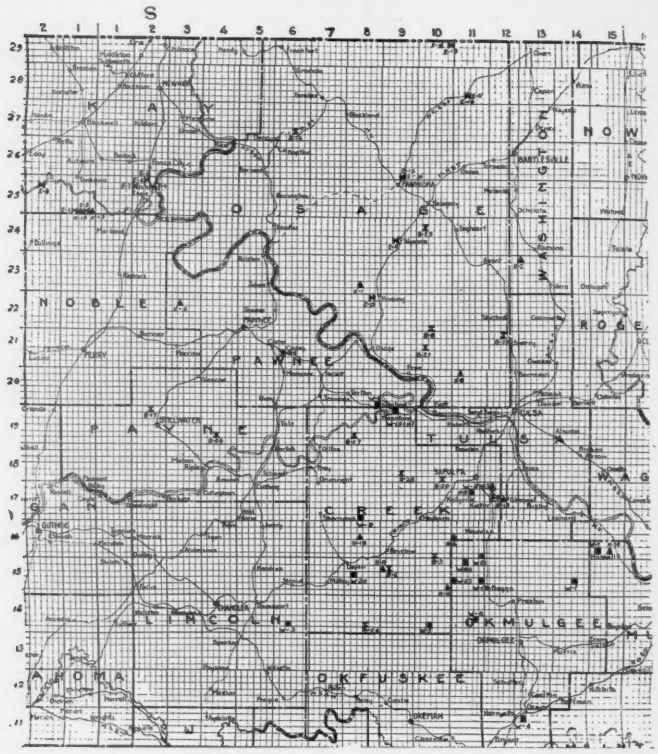

FIG. 1. Map of a portion of northeastern Oklahoma showing the locations of samples analyzed. Squares and W = Wilcox; Triangles and H = Hominy; Double triangles vertical and B = Bartlesville; Double triangles horizontal and E = Elgin.

The analytical work was done by Mr. Mortimore in the sedimentation laboratory of the University of Iowa and with the cooperation of Mr. Trowbridge. The micro-paleontological stud-

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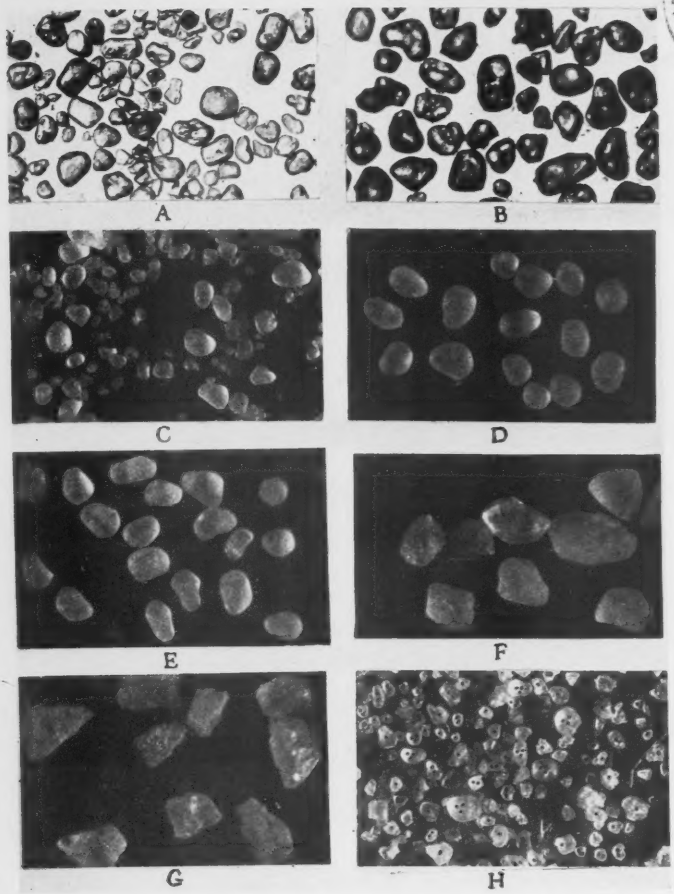


A. Microphotograph of sand immersed in liquid of high refractive index; transmitted light; sample H-6.

B. Microphotograph of sand by transmitted light without immersion; sample H-6.

C. Microphotograph of sand by reflected light with grains on black background; sample H-6.

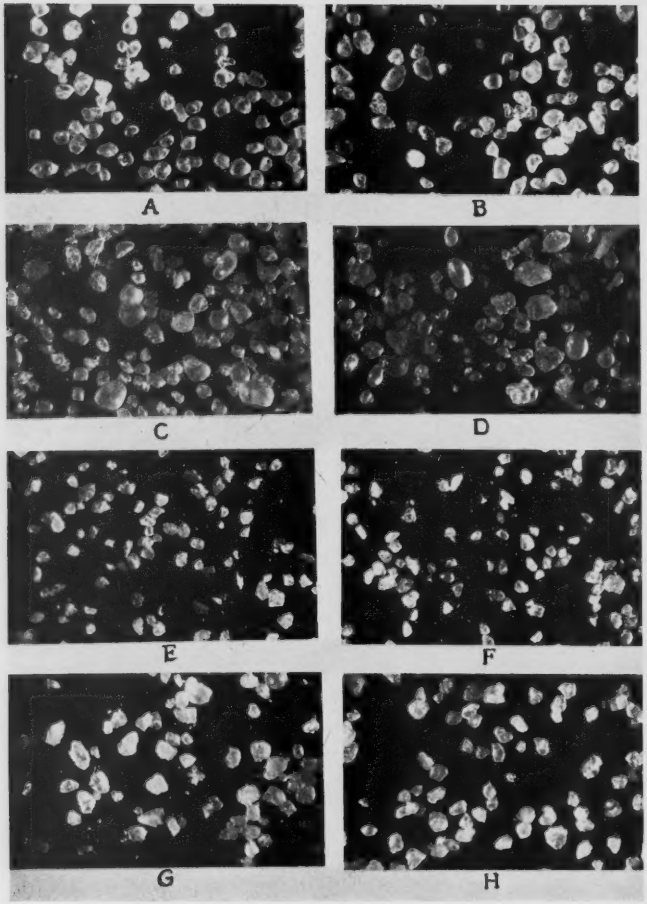
D. Microphotograph showing *rounded* grains.

E. Microphotograph showing *fairly well rounded* grains.

F. Microphotograph showing *subangular* grains.

G. Microphotograph showing *angular* grains.

H. Microphotograph of whole sample with designation of grains into four shape grades. Grains marked with three dots are *rounded;* grains marked with two dots are *fairly well rounded;* grains marked with one dot are *subangular;* grains not marked are *angular.*



A and *B*. Microphotographs of Wilcox sands. *A* is W-5, *B* is W-21.
C and *D*. Microphotographs of Hominy sands; *C* is H-13; *D* is H-1.
E and *F*. Microphotographs of Bartlesville sand; *E* is B-24, *F* is B-25.
G and *H*. Microphotographs of Elgin sand; *G* is E-2, *H* is E-16.

ies were made by Mr. Mortimore under the direction of Dr. A. O. Thomas, and the mineralogical studies under the direction of Dr. J. J. Runner.

METHODS OF ANALYZING.

The physical characters of sands of greatest correlative value are sizes of grains, shapes of grains, and mineral content.

Photographing.—Because the general appearance of a sand under the microscope serves to check criteria for correlation and because shape analysis can best be accomplished by reference to photographic enlargements of grains, the first step in the study of these sands was the making of a microphotograph of a portion of the whole sample. Three types of microphotograph were tried.

One was obtained by use of transmitted light with the sand immersed in a refractive liquid with index either much lower or much higher than quartz. As shown in Pl. I., *A*, this process makes the grains stand out in relief. This method may be preferred by some because of superior qualities for reproduction, but the actual surfaces of the grains are not well shown and the pictures should be taken on Process films necessitating long exposures. Also, transmitted light was tried without immersion of the sand (Pl. I., *B*) but proved on the whole less satisfactory than others because the picture does not show the actual shapes of the grains well.

The type of photograph adopted for this work (Pl. I., *C*) shows the white grains on a black background and appears much as do the sands under the binocular microscope. They were taken with a common camera and a Leitz petrographic microscope, using a microscope magnification of sixteen diameters. The camera was mounted on a stand in a vertical position above the microscope. The sands were sprinkled on a glass plate above black paper on the stage of the microscope and illuminated by two 100 Watt lights, one on either side and close to the stage. The time of exposure was about two minutes with Eastman superspeed film.

Mechanical Analysis.—The percentage of each size grade was determined by weighing a fractioned portion of the sample, sieving, and then weighing each separate grade. The openings of the sieves were in millimeters and fractions of a millimeter in the following sequence: 2, 1, 1/2, 1/4, 1/8, and 1/16. The sieves were shaken by hand.

Shape Analysis.—Four degrees of rounding of grains were recognized; namely, *rounded* (Pl. I., *D*), *fairly well rounded* (Pl. I., *E*), *subangular* (Pl. I., *F*), and *angular* (Pl. I., *G*). The percentages of the shape grades in each sample were determined by marking a microphotograph of the unsieved sample as shown in Pl. I., *H*, and then counting the grains and figuring percentages.

Mineral Analysis.—The heavy minerals in each size grade were first isolated by bromoform separation. The sand was poured into a small evaporating dish containing bromoform of a density of approximately 2.8 in which both quartz and calcite float, the heavy minerals settling to the bottom. The bromoform with the floating minerals was then decanted into a filter and recovered for further use. A small amount of bromoform was used to wash off any light minerals sticking to the sides of the dish and this was in turn added to the filter. The sand in the filter was washed with benzol and dried. The heavy minerals left in the dish were then washed with benzol and dried. Quartz was separated from calcite by using a benzol-bromoform mixture having a density between those of the two minerals and feldspar from quartz in a similar manner.

The different minerals were identified microscopically by the use of common petrographic methods such as are described by Milner and Harker.

Faunal Analysis.—While studying the several size grades of each sample under the microscope in the making of shape and mineral analyses, a sharp lookout was kept for micro-fossils. In these sands almost all the fossils were found in the 1/4–1/8 millimeter size grade. In most cases the fossils consisted of hematite or pyrite and came down with the heavy minerals in

bromoform. They were studied with the binocular microscope and drawings were made of them with a magnification of twenty-five or thirty times. The determination of genera and particularly of species in most cases was difficult because of the fragmental condition of the material and the poor preservation of external markings.

METHODS OF RECORDING.

Because there is no recognized standard method of recording the size, shape, and mineral content of sand grains quantitatively, it was necessary to devise methods which could be used for purposes of comparison. These served fairly well and it is hoped that they will be at least suggestive to others working in this field.

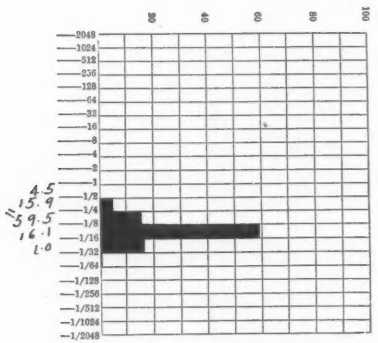


FIG. 2. Record card for mechanical analysis of sediments used in the sedimentation laboratory of the University of Iowa.

The Mechanical Analysis Graph.—For recording the percentages of the several size grades of each sample as determined by sieving, the block diagram or pyramid was chosen. Hundreds of samples of sediments mechanically analyzed in the sedimentation laboratory of the University of Iowa have been thus recorded on cards as shown in Fig. 2, and a project is now under way to reduce to this same form all published mechanical analyses.

For purposes of correlating oil sands, in connection with which the time element both in analyzing and recording must be reduced

to a reasonable minimum, it is thought that the pyramids are more practical than cumulative curves and that they serve quite as well for comparison.

The Shape Analysis Graph.—After the percentages of the shape grades had been determined as previously described, they too were plotted on block diagrams as illustrated and explained in Fig. 3. Although this method of determining and recording

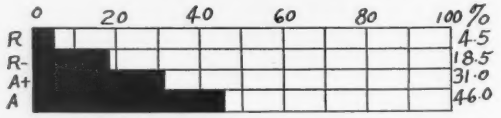


FIG. 3. A shape analysis graph of Sample H–1. *R*, rounded; *R*—, fairly well rounded; *A*+, subangular; *A*, angular.

shapes of grains does not entirely eliminate the personal element and does not set up rigid shape definitions, marking the grains on a print serves to show by what standards the shapes of grains are measured by the individual analyst and at least rough shape analyses are secured for comparison. Also it is possible by this method for one analyst to check another, thus reducing the effect of differences in personal opinion.

The Mineral Analysis Graph.—In the sands studied the

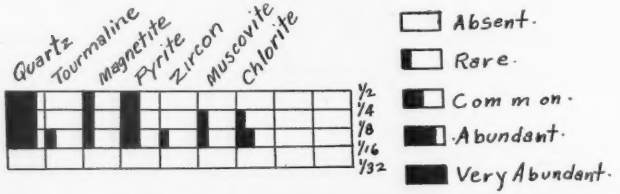


FIG. 4. Record of mineral analysis of Sample B–26.

amounts of heavy minerals are too small to give percentages that could be shown by ordinary graphs, and a somewhat different method had to be used. The record of a typical mineral analysis is shown in Fig. 4. The amounts of the different minerals in

the sample are shown in four grades: *rare, common, abundant,* and *very abundant.* These divisions were based on the number of grains in 1 per cent. of the analyzed sample according to the following scale:

Rare	1–10	grains in 1 per cent. of the analyzed sample
Common	10–30	grains in 1 per cent. of the analyzed sample
Abundant	30–100	grains in 1 per cent. of the analyzed sample
Very abundant.....	100 +	grains in 1 per cent. of the analyzed sample

Quartz was arbitrarily said to be "very abundant" in a sample if it made up more than 90 per cent. of the whole and to be "abundant" if it made up less than 90 per cent. of the whole. Fig. 4 shows the relative amounts of the several minerals in each of the three size grades: 1/2–1/4, 1/4–1/8, 1/8–1/16.

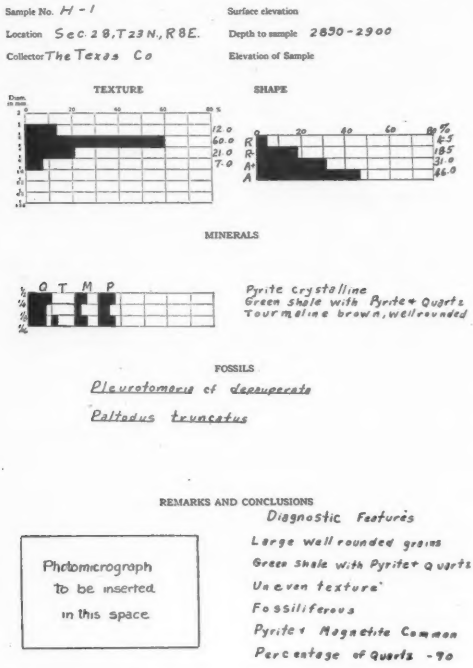


FIG. 5. General analytical record for Sample H–1.

Complete Analytical Record for Each Sample.—After each sample had been photographed and studied for size, shape, and mineral and fossil content, a general record for the whole sample was made on a single 8½ x 11 inch sheet, as shown in Fig. 5.

RESULTS OF ANALYSIS OF THE FOUR SANDS.

General Characters.—Typical microphotographs of the Wilcox, Hominy, Bartlesville, and Elgin sands are shown in Pl. II. The Wilcox (*A* and *B*) is an even-textured fine sand and has many fairly well rounded grains but no large well rounded ones. The Hominy sand (*C* and *D*) is coarser than the Wilcox and has an uneven texture and the large grains are well rounded. The Bartlesville (*E* and *F*) appears as a fine angular sand and the Elgin (*G* and *H*) is more angular and somewhat coarser than the Bartlesville.

Size Grade Distribution.—Mechanical analyses of fifteen samples of each of the four sands are given together in Fig. 6. The Wilcox is a well sorted sand with about 70 per cent. in the 1/4–1/8 millimeter grade. With the exceptions of Samples H–11 and H–9, the Hominy samples have the major size grade between 1/2 and 1/4 millimeter and this sand is on the whole not quite so well sorted as the Wilcox sand. The major size grade in the Bartlesville sand is the same as in the Wilcox sand, 1/4–1/8 millimeter, but the Bartlesville is not nearly so well sorted as the Wilcox. The Elgin is on the average coarser and better sorted than the Bartlesville but not so well sorted as the Wilcox and not as coarse as the Hominy.

It should not be understood that these four sands can be distinguished by texture alone but the fifteen mechanical analyses of each of the sands are nearly the same and there are apparent textural differences between the different sands taking the mechanical analyses either individually or collectively.

Shapes.—Shape analyses of the fifteen samples of each of the four sands are given in Fig. 7 which shows the following outstanding differences: (1) Well rounded grains are found in the Hominy sand only; (2) the Wilcox has nearly equal amounts of

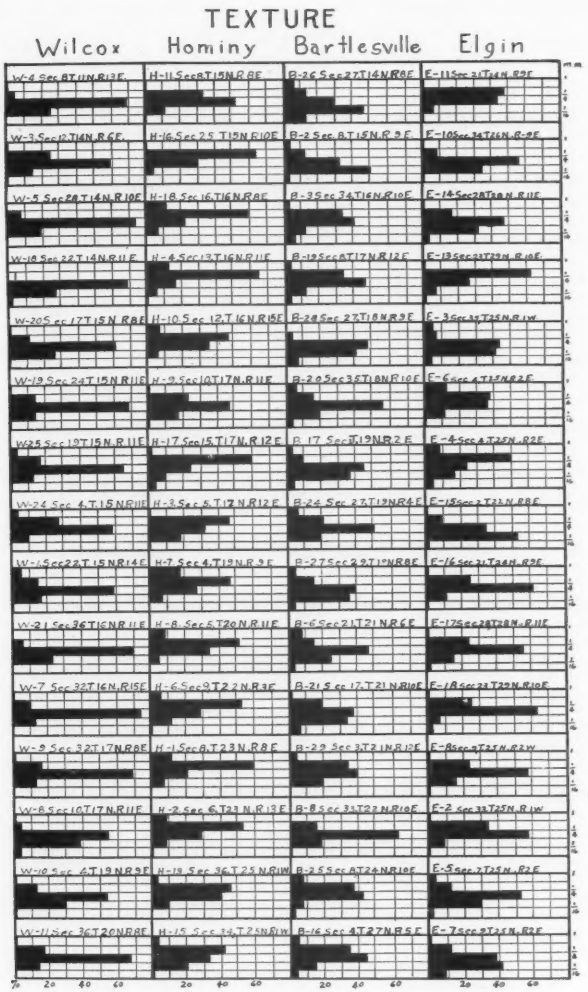


FIG. 6. Mechanical analyses of 60 samples divided equally among the Wilcox (W), Hominy (H), Bartlesville (B), and Elgin (E) sands.

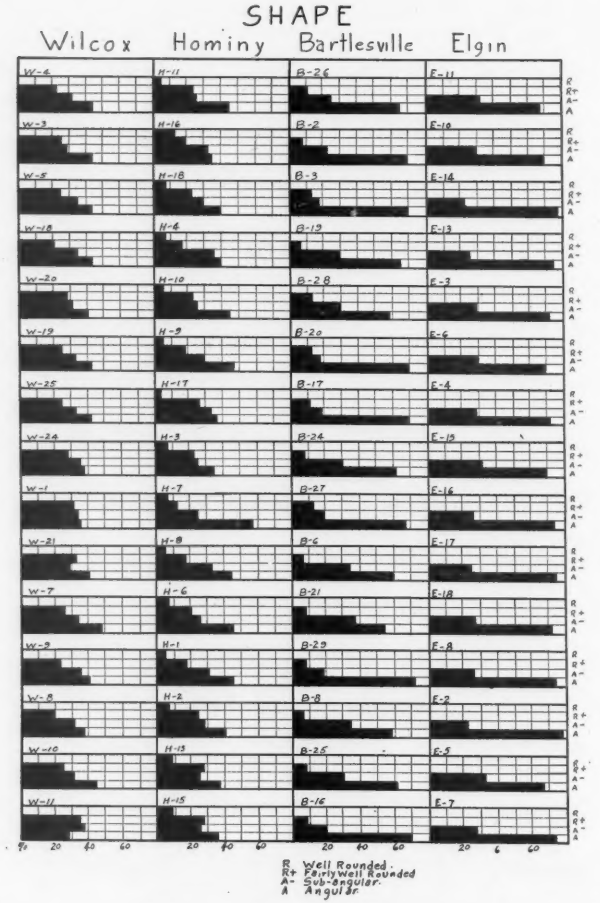


FIG. 7. Shape analysis graphs of the fifteen samples of each of the four sands, for comparison and contrast.

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the three more angular shape grades and no well rounded grains; (3) the Bartlesville is angular but has a small percentage of fairly

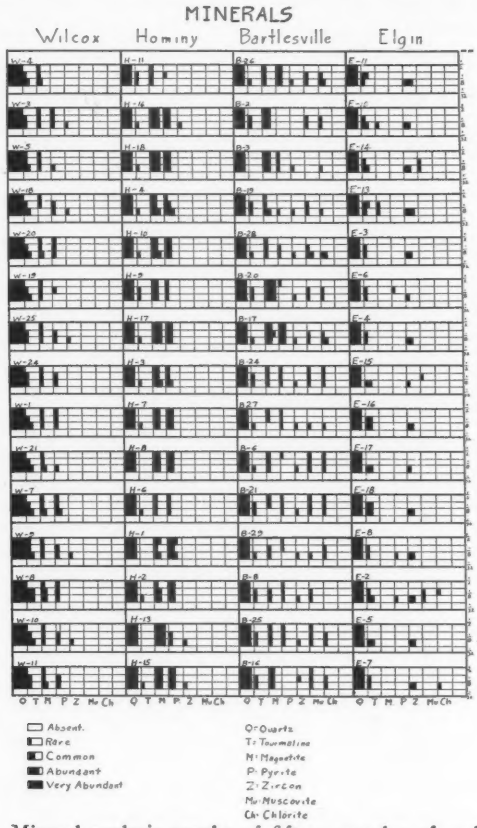

FIG. 8. Mineral analysis graphs of fifteen samples of each of the four sands.

well rounded grains; and (4) the Elgin sand is very angular and has no rounded or fairly well rounded grains.

Minerals.—Fig. 8 shows the mineral content of each of the four sands as determined by mineral analysis of the fifteen sam-

ples of each. The chief points brought out by the analyses are (1) the presence in the Wilcox of tourmaline in both the 1/4–1/8 and the 1/8–1/16 millimeter size grades although in the Hominy it occurs only in the 1/8–1/16 millimeter grade; (2) the highest percentage of magnetite and pyrite in the Hominy; (3) the presence in the Bartlesville of chlorite and muscovite and the

Hominy Fauna

Magnified 25-30 times		H-11	H-16	H-18	H-4	H-10	H-9	H-17	H-3	H-7	H-8	H-6	H-1	H-2	H-13	H-15
	Simple Coral			x	x											
	Polygnathus cf. pennatus			x	x				x				x			
	Polygnathus sp		x	x												
	Polygnathus cf dubius		x	x		x										
	Palmodus truncatus		x	x	x	x	x	x	x	x	x		x			
	Bryozoa				x											
	Pleurodomaria cf depauperata		x	x		x		x	x			x				
	Clenodonta sp			x			x		x							
	Orthoceras sp		x	x	x											x
	Ostracod			x	x	x		x	x							x

FIG. 9. A tabular diagram illustrating and naming generically the fossils making up the Hominy fauna and giving their distribution among the fifteen Hominy samples studied.

rarity of zircon; and (4) the relative abundance of tourmaline and zircon in the Elgin sand.

Fossils.—Practically no fossils were found in the Wilcox, Bartlesville, and Elgin sands, but a few fairly well preserved forms occur in the Hominy, as shown in Fig. 9.

SUMMARY.

The data by which the four sands can be correlated and by which an "unknown" can be identified are summarized in Fig. 10. The numbers in the fossil column represent the number of species in the sample. "Well sorted" is used for all samples

having more than 60 per cent. in one size grade. If more than 50 per cent. of a sample falls in the angular and subangular shape grades it is designated as "angular." The letters in the mineral

Sample No.	Location	Fossils	Well Sorted	Recrystallized	Angular Qtz. + Rounded Grains	Green Shale Fragments	Chlorite	Muscovite	Magnetite	Pyrite	Pyrite Crystals	Quartz 90° +	Zircon Crystals	Zircon Angular	Zircon Rounded	Tourmaline Crystals	Tourmaline Angular	Tourmaline Rounded
W-4	Sec. 8 T. 11 N. R. 18 E.	X							C			X						C
W-3	Sec. 28 T. 14 N. R. 6 E.	X							R	R		X						R
W-5	Sec. 28 T. 14 N. R. 10 E.	X							R	R		X						C
W-18	Sec. 22 T. 14 N. R. 11 E.	X							C	R		X						C
W-20	Sec. 17 T. 15 N. R. 8 E.	X							C	R		X						C
W-19	Sec. 24 T. 15 N. R. 11 E.	X							R	R		X						C
W-25	Sec. 19 T. 15 N. R. 11 E.	X							R	R		X				R		R
W-24	Sec. 4 T. 16 N. R. 11 E.	X							R	R		X						R
W-1	Sec. 23 T. 19 N. R. 4 E.								R	R		X						C
W-21	Sec. 36 T. 16 N. R. 11 E.	X							C	R		X						C
W-7	Sec. 32 T. 16 N. R. 15 E.	X							C	C		X						C
W-9	Sec. 32 T. 17 N. R. 8 E.	1	X						R	R		X				R		C
W-8	Sec. 10 T. 17 N. R. 11 E.								C	R		X						C
W-10	Sec. 6 T. 18 N. R. 9 E.	1							R	R		X						C
W-11	Sec. 36 T. 20 N. R. 8 E.		X						C	R		X						C
H-11	Sec. 8 T. 15 N. R. 8 E.	1				X	X		R	R							R	R
H-16	Sec. 25 T. 15 N. R. 10 E.	6	X			X	X		A	C							R	R
H-18	Sec. 16 T. 16 N. R. 8 E.	8				X	X		A	C	X						R	R
H-6	Sec. 13 T. 16 N. R. 11 E.	9	X			X	X		A	A	X					R	R	R
H-10	Sec. 12 T. 16 N. R. 15 E.	3				X	X		A	C	X					R	R	R
H-9	Sec. 10 T. 17 N. R. 11 E.	1				X	X		C	R	X						R	R
H-17	Sec. 15 T. 17 N. R. 12 E.	3	X			X	X		A	C	X						R	R
H-3	Sec. 6 T. 17 N. R. 12 E.	3				X	X		A	C	X						R	R
H-7	Sec. 6 T. 19 N. R. 9 E.	3			X	X	X		C	C	X						R	R
H-8	Sec. 5 T. 20 N. R. 11 E.	1				X	X		C	C	X					R	R	
H-6	Sec. 9 T. 22 N. R. 3 E.					X	X		R	R	X						R	R
H-1	Sec. 28 T. 23 N. R. 8 E.	2	X			X	X		C	A	X						R	
H-2	Sec. 6 T. 23 N. R. 13 E.					X	X		C	C	X					R	R	R
H-19	Sec. 36 T. 25 N. R. 1 W.	1				X	X		A	C	X					R	R	C
H-15	Sec. 34 T. 25 N. R. 1 W.	3				X	X		C	C	X							R
B-26	Sec. 27 T. 14 N. R. 8 E.				X													
B-2	Sec. 8 T. 15 N. R. 9 E.				X			R		C								R
B-3	Sec. 34 T. 16 N. R. 10 E.				X			R		R	R					R	R	R
B-19	Sec. 8 T. 17 N. R. 12 E.				X			R	R	C	R					R	R	R
D-28	Sec. 27 T. 18 N. R. 9 E.				X			C	C	R	R					R		R
B-20	Sec. 35 T. 18 N. R. 10 E.				X			R	R	A	R					R	R	R
B-17	Sec. 3 T. 19 N. R. 2 E.				X			C	R	C	C					R	R	R
B-24	Sec. 27 T. 19 N. R. 4 E.	2			X			R	R	R	R					R	R	R
B-27	Sec. 29 T. 19 N. R. 8 E.				X			R	R		R					R	R	
B-6	Sec. 21 T. 21 N. R. 6 E.				X			R	R	R	R					R	R	R
B-21	Sec. 12 T. 21 N. R. 10 E.				X			R	R	R	R					R	R	R
B-29	Sec. 4 T. 21 N. R. 12 E.				X			R	R	R						R		R
B-8	Sec. 33 T. 22 N. R. 12 E.				X			R	R	R						R	R	R
B-25	Sec. 4 T. 24 N. R. 10 E.				X			R	R	R	R						R	R
B-16	Sec. 4 T. 27 N. R. 5 E.				X			R	R	C						R	R	R
E-11	Sec. 31 T. 28 N. R. 9 E.				X											A	A	C	C	R
E-10	Sec. 36 T. 26 N. R. 9 E.				X											C	C	C	C	C
E-14	Sec. 24 T. 29 N. R. 11 E.				X											A	A	C	C	R
E-13	Sec. 33 T. 29 N. R. 10 E.				X			R								A	A	C	C	R
E-3	Sec. 11 T. 25 N. R. 1 W.				X							R				C	C	C	R	R
E-6	Sec. 4 T. 25 N. R. 2 E.				X											C	C	C	R	R
E-4	Sec. 6 T. 25 N. R. 2 E.				X			R								C	C	C	R	R
E-15	Sec. 2 T. 22 N. R. 8 E.				X			R								C	C	C	A	R
E-16	Sec. 24 T. 28 N. R. 9 E.				X											A	A	C	C	
E-17	Sec. 28 T. 28 N. R. 11 E.				X															
E-18	Sec. 28 T. 29 N. R. 9 E.				X											C	C	C	C	C
E-8	Sec. 17 T. 25 N. R. 1 W.				X						R					A	A	C	R	R
E-2	Sec. 33 T. 25 N. R. 1 W.				X			R	R		R					A	A	C	C	C	R
E-5	Sec. 2 T. 25 N. R. 2 E.				X			R								C	C	C	C	R	R
E-7	Sec. 9 T. 25 N. R. 2 E.				X											C	C	C	R	R

FIG. 10. Chart summarizing the criteria for recognition of the four sands. Figures = No. of fossil species, x = present, R = rare, C = common, A = abundant.

columns designate whether the given mineral in each sample is absent, rare, common, abundant, or very abundant.

Thus each of the four sands has its own characteristics by a combination of which it can be identified, as follows:

The Wilcox Sand:

1. General appearance under microscope as in Pl. I., *D* and *E*.
2. Well sorted, with 55 per cent. to 75 per cent. in the 1/4–1/8 millimeter grade.
3. Angular, subangular, and fairly well rounded grains in about equal proportions and contains no well rounded grains.
4. Muscovite absent, magnetite rare to common, pyrite rare, rounded tourmaline common, more than 90 per cent. quartz.
5. Practically unfossiliferous.

The Hominy Sand:

1. General appearance as in Pl. I., *F* and *G*.
2. Fairly well sorted, with 40 per cent. to 65 per cent. in the 1/2–1/4 millimeter grade. Coarser than the Wilcox sand.
3. Is the only one of the four sands to contain large well rounded grains.
4. Contains fragments of green shale.
5. Muscovite absent, magnetite in variable amounts, crystallized pyrite common, tourmaline angular and well rounded.
6. Contains a limited but recognizable micro-fauna.

The Bartlesville Sand:

1. General appearance as in Pl. II., *E* and *F*.
2. Not well sorted.
3. Angular grains greatly predominate but contains a small percentage of fairly well rounded grains.
4. Muscovite rare or common, magnetite rare, tourmaline and zircon rare in crystals, angular grains and rounded grains, chlorite present.
5. Practically unfossiliferous.

The Elgin Sand:

1. Appears as in Pl. II., *G* and *H*.
2. Not well sorted.
3. Angular grains greatly predominate and contains no rounded or fairly well rounded grains.
4. Zircon and tourmaline common in crystals, angular grains and rounded grains.
5. Unfossiliferous.

CONCLUSIONS.

It is the opinion of the writers that it is possible to differentiate these four sands by physical characters alone. It seems probable that most of the Paleozoic sands at least possess such constant or uniformly varying characters that comparison with or interpolation in a known series of analyses will permit the correct placing and correlation of most specimens analyzed. This is dependent, of course, on several factors, such as: availability of the complete section in which the specimen is likely to occur, previous analyses for comparable results, specimens of the sand areally distributed to provide knowledge of its variations, selection of the diagnostic characters correctly, etc. However, with the differentiating characters known, there will be only one horizon to which any sample can be assigned. The purpose of this paper is to suggest certain characters which have been found diagnostic in the cases given, and the methods in brief by which these have been determined.

Experience in the sedimentation laboratory has shown the presence of certain geographic and geologic limitations to the application of the methods here outlined. Universal application is not claimed, but confidence is held in the value of such work in sub-surface correlation particularly. As an aid to the paleontologist and general geologist its value is self-evident.

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A MAGNETITE SEGREGATION IN BANDED SYENITE IN MINNESOTA.[1]

FRANK F. GROUT.

INTRODUCTION AND GENERAL FEATURES.

MINNESOTA has long been known for its titaniferous magnetites in gabbro, and recently there have been reported some magnetite pegmatites related to granite. This note concerns an occurrence, though probably not a commercial one, of a band of magnetite segregated in a banded syenitic early phase of the Algomian granite batholith of northern St. Louis County, Minnesota. The deposit was briefly mentioned in an earlier Survey report,[2] but it was then supposed to be a phase of the Keewatin.

The deposit is located in the southwest quarter of the northwest quarter of section 4, Township 63 north, Range 12 west, north of Ely, Minnesota. Several test pits were opened many many years ago, but since the timber was cut a dense growth of brush has sprung up and the outcrop is not easily found.[3]

The country rock for about a mile each way is banded and syenitic. The general setting in the surrounding region is shown in Fig. 1. The Keewatin greenstone and its included iron formation are more than a mile away to the south. The Knife Lake slates occur in and near the areas of greenstone as synclinal belts. Igneous intrusive magmas have turned much of the slate to mica schist. A few yards south of the syenite in which the ore band occurs is a narrow belt of granite gneiss which is intruded by

[1] Published by permission of the Director of the Minnesota Geological Survey.

[2] Winchell, N. H., and H. V., Minn. Geol. and Nat. Hist. Survey Bull. 6 pp. 7–24 (1891). The magnetite rock is described as having "supposed igneous characters, but these are found sometimes to fade out, and a sedimentary lamination to supervene."

[3] Winchell (*op. cit.*) notes that he had to be guided.

the syenite. North of the syenite is the great Vermilion granite which in places intrudes the syenite. In other places the syenite seems to grade into the granite; and this, in connection with its position along the borders of the granite, makes it evident that the syenite is an early differentiate of the granite magma.

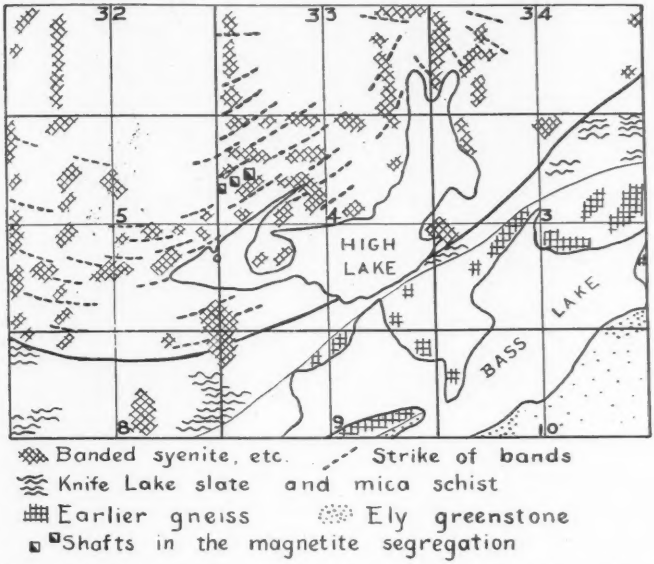

FIG. 1. Map of outcrops in Sec. 4, T. 63 N., R. 12 W, showing the test pits in magnetite and their surroundings.

The largest development of syenite around the granite batholith is found on Basswood Lake, along the international boundary. A relatively narrow belt extends westward to High Lake, and intermittently for many miles farther west. Near High Lake the syenite is more banded, and has a greater proportion of dark minerals than in most places. The bands include some petrographic types that are rare as phases of granite batholiths.[4]

[4] Grout, Frank F., "A Peculiar Shonkinite Related to Granite, *American Jour. Science* (In Press).

Near the ore, several bands of the rock are especially rich in dark minerals, grading to hornblendites, but those tested were

FIG. 2. An outcrop of banded syenite near High Lake, Minnesota. This is the country rock of the magnetite deposit.

found to contain less than 10 per cent. magnetite. Most of the feldspar in the banded rock is orthoclase and oligoclase; but a few bands contain andesine and should be classed as diorite.

THE ORE.

The band of ore is about four feet wide and has been traced by test pits for perhaps 200 yards. It is banded like its wall rocks, with varying amounts of magnetite and silicates in the several bands. The elongated crystals are partly oriented in the direction of the bands. Both strike N. 60° E. and dip nearly 90°. In one test pit the ore is cut by aplite, such as is common in both the syenite and the related granite.

The ore consists of magnetite, ilmenite, hornblende, green spinel, and a very light brown biotite, with a little pyrite and allanite as accessories.

The magnetite is partly, if not wholly, late to crystallize. It surrounds and in places cuts across the silicates. Ilmenite is in subhedral grains of about the same size as the grains of magnetite, not intimately intergrown with the magnetite along crystal-

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lographic planes, as it commonly is in gabbro ores. The hornblende is of the common green variety, with a mean index of refrection, beta $=1.672 \pm 2^5$. Biotite in the ore is very light colored and has an index of refraction gamma $= 1.610 \pm 5$. This indicates that the iron of the magma was in some way con-

FIG. 3. A section of lean ore. Gangue minerals are hornblende and biotite.

centrated into the magnetite leaving relatively little in the mica.[6]

Green spinel is abundant only in a few of the richer ore bands. The composition of the ore is approximately shown by the following analysis, made for the Survey by the Minnesota School of Mines Experiment Station. An older analysis on material of less certain origin is added for comparison.

Note should be made of the titanium content. This was not found in the older work, and its absence led to a suspicion that the ore was not strictly igneous.

[5] Winchell, A. N., "Studies in the Amphibole Group," *Am. Jour. Sci.*, vol. 7, pp. 287–310, 1924.

[6] Grout, Frank F., "Notes on Biotite," *Amer. Mineralogist*, vol. 9, pp. 159–165, 1924.

	1	2
SiO_2	5.69	10.90
Al_2O_3	7.23	5.83
Fe_2O_3*	46.92	70.39
FeO*	27.87	8.75
MgO	3.70	1.50
CaO	1.03	1.20
Na_2O	.28	
K_2O	.24	
H_2O+	1.17	
CO_2	.26	
TiO_2	5.97	none
CoO	.07	
NiO	.09	
Cr_2O_3	.03	
V_2O_5	.49	
S	.02	.47
P_2O_5	.02	.02+
MnO	.26	none
	101.42	99.06

1. Sample collected in Sec. 4, T. 63 N., R. 12 W., Minnesota, by F. F. Grout. J. H. McCarthy, analyst.

2. Specimen obtained from Mr. Mallman. J. A. Dodge, analyst.

* Total Fe = 55.39, Magnetic Fe, 49.28. Tabulated results have been recalculated.

ORIGIN OF THE ORE.

In the first place, the idea of pegmatitic origin is not favored because the pegmatites of the same batholith have some non-titaniferous magnetite prospects, of very different character from these.[7]

In the second place, hydrothermal effects are not conspicuous and some of the richest ore is associated with igneous minerals with practically no signs of alteration.

The field occurrence of the magnetite band in banded syenite is almost conclusive evidence of its origin by igneous segregation. The occurrence of the magnetite band where most of the other bands are especially dark and ferruginous, is confirmatory. Its igneous textures and minerals agree. The process by which

[7] Grout, Frank F., "Magnetite Pegmatites of Northern Minnesota," ECON. GEOL., vol. 18, pp. 253–269, 1923.

it segregated and attained its present vertical position still requires discussion.

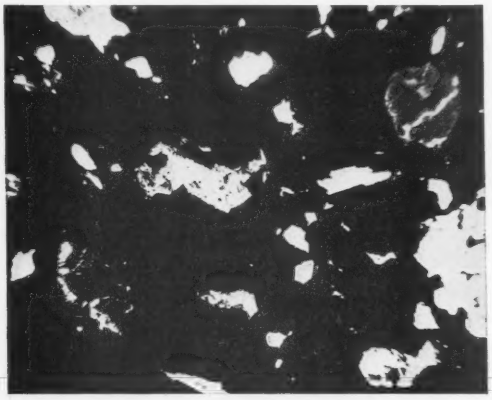

FIG. 4. A section of rich ore. Gangue minerals; gray grain is spinel; lighter grains are biotite and hornblende.

At this point the degree of concentration should be noted. While the main granite of the batholith has only about 1 per cent. of iron, the ore was probably segregated at an early stage represented by the syenite with 5 per cent. or more of iron. From this magma, segregation has produced bands which show 20 to 65 per cent. of magnetic iron, as estimated from measurements of thin sections. Evidently at a certain stage magnetite crystallized much more abundantly than it did before or after. The evidence appears in the thin sections, showing that magnetite was not first to crystallize, and in the field occurrence of the ore between layers of other rock types—not at the base or border of the igneous rock.

The texture and structure of the ore are conclusive evidence of motion during crystallization. The motion was probably in the nature of a convection, for the banding is associated with a fluxion structure.[8]

[8] Grout, Frank A., "Internal Structures of Igneous Rocks," *Jour. Geol.*, vol. 26, pp. 439–458, 1918.

Attention may well be called to the theoretical significance of this case, for the magnetite can not be supposed to have accumulated by crystal settling. It stands as a nearly vertical sheet and could not have settled into such a position. Neither could it have been a horizontal sheet resting on a floor, for batholiths are not known to have such floors. The ore crystals evidently accumulated along the cooling wall of the batholith at the particular time when conditions especially favored the crystallization of magnetite in the circulating magma.

ECONOMIC FEATURES.

The ore-body now known is too small to be of much interest, and the exploration conducted years ago probably proved that no greater volume is to be expected here. Other bands of the same sort, however, are not unlikely.

The magnetism of the ore makes it possible to concentrate even the leaner portions to a rich concentrate. The injurious impurities are easily removed in the process, chiefly because ilmenite is in coarse grains. The magnetite grains, however, range about 0.5 mm. in diameter, with some rather smaller, so that fine grinding would be necessary for a large recovery. A test made by the Minnesota School of Mines Experiment Station, using a magnetic washer, and ore ground to 100 mesh, gave 71.6 per cent. of concentrate which contained 68.83 per cent. iron, .92 per cent. titanium oxide, and .010 per cent. phosphorus.

The search for tonnage, then, is the first step in any further consideration of these ores. Rumors have come to the Survey, of some iron ore in sections 33 and 34, T. 64 N., R. 12 W., just north of this deposit; but no ore has been seen there by Survey parties. Some dark bands of hornblendite like those in section 4 cross the area. The more extended search for such ore, if attempted, should be directed to the area of syenite of Basswood Lake and other such syenites near the Vermilion granite.[9]

[9] Not to the greenstone and other inclusions in the granite, as suggested by Winchell, *op. cit.*, p. 24.

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RELATIONSHIPS IN MINERAL DEPOSITS IN NORTHWESTERN MANITOBA.

R. C. WALLACE.

INTRODUCTION.

THE unravelling of the genetic relationships of the ore-bodies in mineral provinces is a study on which in recent years much work has been done. J. E. Spurr has done the science of geology a notable service in outlining in several publications[1] the succession of ore-types which may form at increasing distances from the parent batholith. From that point of view, he has discussed[2] somewhat fully certain phases of mineralization in that area in northwestern Manitoba that extends from lake Athapapuskow eastwards to Wekusko (Herb) lake. The genetic

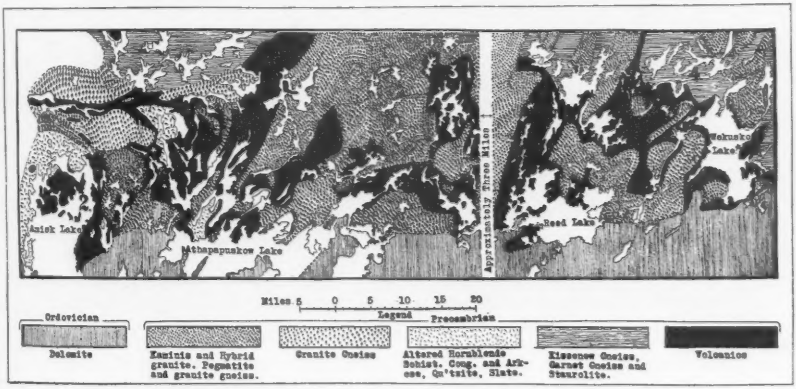

FIG. 1. Amisk, Athapapuskow, Reed, and Wekusko Lakes Region. 1, copper, lead, zinc, iron sulphides; 2, gold (arsenopyrite); 3, gold (pyrite and galena); 4, argentiferous galena, stibnite; 5, gold (tourmaline, arsenopyrite).

[1] See in particular "The Ore Magmas" (McGraw Hill) 1923.
[2] Ibid., Chap. II.

relationships of the somewhat diverse types of mineralization in that area are of considerable interest, and are dealt with in detail in the present paper.

GEOLOGICAL FEATURES.

The area has been mapped for the Geological Survey of Canada by E. L. Bruce [3] and F. J. Alcock.[4] The essential relationships of geological formations are reproduced in the accompanying map (Fig. 1) based on Bruce's and Alcock's maps, but correlating certain formations represented by distinctive local names in the two map sheets. A granite, normally massive but in certain areas gneissose, intruded volcanics and associated sediments (Kissenew gneiss, garnet gneiss and staurolite schist) and, as well, later series of sediments (altered hornblende schist, conglomerate and arkose, quartzite, slate), mainly conglomeratic, and unconformably placed on the earlier volcanics and sediments. The mineralization of the whole area, whether in volcanics or sediments, is referred with a measure of certainty to the granites, and on the following grounds. The mineralization is closely associated with the granite, occurring either in the neighboring invaded rock, or, in some instances, in shear zones in the granite itself. The massive granite is found to contain, though rarely, scattered sulphides, particularly arsenopyrite, which is a widely distributed mineral in the area. And, though in special cases basic (lamprophyric) dikes, closely associated with the sulphide replacements, as in the Flin Flon ore-body, might be suggested as the parent body of the sulphides, a survey of the sulphide bodies throughout the area points convincingly to the conclusion that the granite was responsible for the sulphide mineralization as well as the other types of ore-bodies. The Ordovician dolomites, which flank the Pre-cambrian formations to the south, may have extended over the area until Tertiary times, and protected the less resistant ore-formations from the erosion that they would otherwise have undergone.

[3] Geol. Surv. Can. Memoir 105, 1918.
[4] Geol. Surv. Can. Memoir 119, 1920.

TYPES OF MINERALIZATION.

The mineral deposits may be divided into two main types:[5] (*a*) gold quartz veins, (*b*) sulphide replacement bodies. These may be further subdivided as follows:

(*a*) Gold quartz veins:
1. With scheelite and molybdenite, in pegmatites.
2. With arsenopyrite, tourmaline and pyrite.
3. With galena and pyrite.
4. With pyrite and stibnite.

(*b*) Sulphide replacement bodies:
1. Pyrrhotite and pyrite.
2. Pyrite, chalcopyrite, sphalerite.
3. Sphalerite, galena, stibnite.

The gold-bearing quartz veins occur in greatest numbers at the west and east ends of the area: the sulphide bodies mainly from the middle of the area westwards. Some indication is given in the map (Fig. 1) of the position of the principal areas of mineralization, but it must be understood that the mineral deposits are not localized to the extent that this representation of the mineralization would indicate. The above list of types of mineral deposits is arranged in the probable order of decreasing temperature of formation. Their position with reference to the parent magma will be discussed from that point of view.

While the types as above described are fairly definitely recognizable, they are not exclusive of intermediate types, but rather represent distinctive marks in a continuous series. The question of the relationship of the lowest temperature types of quartz veins to the highest temperature types of sulphide replacement bodies requires further discussion, inasmuch as two apparently somewhat dissimilar processes are involved.

To deal first with the quartz veins. They occur in the volcanics, both basic and acid, in the fine-grained sediments (quartzites and mica staurolite schists), and in the granite. They are

[5] "Mining and Mineral Prospects in Northern Manitoba," R. C. Wallace, Northern Manitoba Comm., 1920.

most continuous in the volcanics, least continuous in the granites. They vary, as Spurr has described, from the quartz offshoots from pegmatites, through feldspar-bearing quartz veins, into the typical fissure veins carrying little or no silicate. A still further stage is found in the silicified impregnations frequently though not invariably associated with sulphide bodies, and occurring mainly in acid porphyries near zones of shearing. The mineralization is characteristic, as the above list indicates. The whole area is distinctively an area of arsenopyrite mineralization. Arsenopyrite is found in the veins and as impregnations in the walls, particularly in the second type, but is found in all types of quartz veins, in the granite itself, and even in the sulphide bodies, though sparingly. The parent magmas were abnormally rich in arsenic, and its crystallization was prolonged throughout the duration of the quartz crystallization stage. On the other hand, copper sulphides occur sparingly in the quartz vein stage. Chalcopyrite occurs in Beaver lake veins, but seldom elsewhere. Its crystallization was held back until the sulphides formed as replacement bodies, associated with only limited quartz.

In differentiating the quartz veins according to temperature of crystallization, the occurrences of scheelite, tourmaline, galena, and stibnite are significant. Scheelite is found associated with pegmatites on the west shore of the north arm of Little Herb lake, in irregular quartz veins carrying values in gold. Molybdenite is associated with similar pegmatite quartz veins elsewhere, as in Crowduck bay, and with quartz veins not in pegmatites, as on the west side of Copper lake and at Phantom lake, but has not been noted with the scheelite on Little Herb lake. Molybdenite may occur at distances further removed from the granite parent magma than does scheelite, in the area under discussion. Tourmaline is associated with the quartz veins on the east side of Herb lake, occurring mainly in fissures in the quartz, in close relationship to arsenopyrite, and, not infrequently, to galena. Galena has a wide range: it is found with tourmaline, arsenopyrite, and pyrite in the Herb lake veins, with pyrite and sphalerite in the veins in Twin lake which traverse fine grained porphyry

dikes, with pyrite, occasionally chalcopyrite, or without other sulphides in the wide quartz lodes of the Copper lake area. From its mineralogical relationships and its field occurrences, it seems evident that the crystallization of galena has persisted through a fairly wide range of temperatures. The lowest temperature mineral found in the area in association with quartz and gold is stibnite, in the Broad Bay district of Herb lake, six miles south of the tourmaline-arsenopyrite-galena gold-quartz veins. The only other occurrences of stibnite in this field are in the galena-sphalerite-stibnite replacement deposit in metamorphosed sediments north of little Herb river. In neither case is the deposit of low temperature origin, though the replacement deposit is of lower temperature than the quartz vein. Stibnite must be taken as extending in this field to moderate depths.

It has not been found possible in the field to point to a clear piece of evidence of the gradation of the quartz vein type into the sulphide type of mineralization. The sulphides are frequently associated with much quartz, and the quartz veins are often very rich in sulphides. In the Copper lake area the association of quartz veins with sulphide replacement bodies is very close. The veins are mainly of the galena type, and the sulphides of the pyrrhotite-pyrite type. They are evidently closely connected in origin. It is noteworthy in passing that pyrrhotite is rarely found in quartz veins, and is widespread as a replacement mineral. The specific question of the relationship of quartz veins to sulphide bodies is reserved for fuller discussion in a later paragraph.

The sulphide bodies are very extensive in distribution and in individual size. They are most numerous from Schist lake eastwards to Elbow lake but they are distributed over the whole area. Pyrrhotite, pyrite, arsenopyrite, sphalerite, chalcopyrite, galena, stibnite, occur to varying degree. Arsenopyrite is rare: stibnite occurs only with galena: pyrrhotite, pyrite and chalcopyrite are the most widely distributed of the sulphides. The sulphide bodies consist normally of scattered and disseminated fine grained pyrrhotite and pyrite in the mashed or sheared zones

in the greenstone lavas, or in the associated tuffaceous rocks, making up in bands and lenses, by continuous gradation, into solid sulphide. This is the case at Copper lake, Tramping lake, File lake, and at the northeast arm of Athapapuskow lake. In places, however, sulphides of copper and of zinc occur as well—the copper more widespread than the zinc; though in the Flin Flon ore-body, the most extensive deposit of economic importance in the area, the zinc predominates (3.5 per cent. Zn: 1.7 per cent. Cu). These bodies contain only very little galena. In the almost flat lying sediments bedded with the volcanics at the east end of the belt north of Herb lake, fairly heavy bands of galena, associated with sphalerite and some stibnite, are found in the more arenaceous phases of the metamorphosed sediments. This type of replacement is restricted to this particular area. A different type of mineralization to that which may be taken as normal to the district, is displayed in the east arm of lake Athapapuskow, where chalcopyrite and bornite occur in stringers and veinlets in a highly epidotized greenstone, which has been much hardened during the process of epidotization, a process which was apparently contemporaneous with the invasion of the copper sulphides. The rock had not been sheared or faulted as in the case of the replacement sulphides above described. The copper sulphides were not distributed evenly throughout the body of the rock, but sought the narrow openings and vugs, and by infilling and partial replacement had been deposited in veinlets and masses in the rock. This is exceptional to the general type, and indicates apparently a somewhat higher phase of temperature activity, approximating in some measure to pneumatolytic action.

RELATIONSHIP BETWEEN QUARTZ VEINS AND SULPHIDE DEPOSIT.

In his treatise on Ore Magmas, Spurr discusses the type of vein-filling which is due to the upward movement of the magma, in contradistinction to the vein matter deposited from solutions emanating from the magma. The former he calls vein-dikes. In his discussions of the Northern Manitoba area, Spurr considers the central lens of the Mandy ore-body to be of the

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vein-dike type, in this way correlating the sulphide bodies to some extent with the quartz veins, which are taken to be, in the main, vein-dike as well. Spurr has notably clarified the conceptions of the genesis of the various ore-types, by showing their close consanguinity, and indicating the steps in the gradational series. His application of the principle of vein-dikes to the central part of the Mandy ore-body demands however further analysis.

It has already been noted that the sulphide bodies throughout the area occur in sheared greenstones in the form of replacement deposits. The physical character of the rock, and the degree to which it has been shattered, are factors which seem to be of as great importance as the mineralogical composition of the rock in influencing the replacement. This is particularly to be noted in the Flin Flon ore-body where a horse of massive greenstone which has escaped shearing has not been replaced, and stands unaffected in the midst of the ore-body. Throughout the whole field, with the exception of the chalcopyrite-bornite stringers on the east end of lake Athapapuskow already described, the sulphide bodies have been found to occur in the softer, more mashed, rock. They vary in degree of sulphide concentration from very scattered bunches or individual crystals to masses in which the country rock is not perceptible to the naked eye, and, as a rule, they vary insensibly from the one type to the other. The cumulative evidence from the whole area points to a single type of process—that of the gradual action of heated, sulphide-bearing solutions on the rock which had been made available for replacement by a process of physical attrition through shearing movements. Spurr places full weight on this process throughout the field with the one marked exception —where the main ore lens of the Mandy mine is considered to have been filled by the ore magma itself, thus providing the link between the vein-dikes of quartz and the sulphide bodies. This lens, now excavated, consisted of high grade chalcopyrite (18–20 per cent. Cu) and subsidiary sphalerite and pyrite in a much larger body of low grade chalcopyrite (6 per cent. Cu).

sphalerite, and pyrite. The definition of the lens is fairly sharp, it is placed somewhat athwart the main sulphide body, and the interfingering at the margin with the lower grade sulphide suggests the action of a sulphide magma. The streaky character of the bands of zincblende and chalcopyrite is of the kind that might most readily be formed by a viscous flow. On the other hand, there is sharp definition in the underground workings of the Flin Flon ore-body between the mixed sulphides and the disseminated sulphides, both of which are clearly replacement types, for part of the original rock still remains intermingled with the sulphides. Selective replacement, aided probably by the physical condition of the neighboring rock types, may produce sulphide bodies with adjacent boundaries of knife-like sharpness. In the Mandy ore-body, even in the densest of parts of the high grade lens, very considerable amounts of silicate are found which can be more readily accounted for as the residuals from replaced basic rock than as a part of the rock magma which introduced the sulphide body. In the Flin Flon ore as well, there is a streakiness in the replaced ore which resembles in nature, though not in degree, the bands in the Mandy ore which seem to indicate viscous flow. It is the cumulative evidence throughout the field of that similarity in kind, though gradations in degree, of the process of replacement of volcanic rock by sulphide which, in the writer's mind, is the real difficulty in accepting a different explanation for an ore-body, which differs in degree of concentration of sulphide rather than in other essential features. The difference between a sulphide magma and a solution from which sulphide replacement could take place is itself one of degree. Both are solutions; they differ in the quantity of material in solution, and the temperature at which the solution is injected. They would differ essentially however in the manner of injection. The vein-dikes may be supposed to make way for themselves by widening the fissures into which they come, much as a granite batholith makes way for itself by pressure movements. The fluid sulphide solutions, on the other hand, permeate the rock which they invade as they would a sponge, and make way for

themselves by actual replacement of mineral material. It is on that somewhat fundamental difference of physical mode of intrusion that the above discussion has been based.

The relationship of the sulphide bodies to the gold-bearing quartz veins is to be traced, in the writer's view, not through sulphide vein-dike, but in the continuous removal of silica from the solutions, their consequent increased fluidity, thus enabling them to penetrate through, and replace, the country rock. Some silica is deposited with the sulphides, and some sulphides with the quartz veins; but there is on the whole a fairly clear-cut dividing line between the two classes of deposits, which would seem to correspond to a physical difference in the degree of viscosity of the solutions. The sulphide bodies would thus represent the residuals from a high temperature solution from which the silica had been precipitated as quartz, and might even represent a concentration of the sulphide-rich solutions independent to some degree of high silica concentration. There is, in other words, a general sequence from quartz vein to sulphide body in the order of falling temperature; but there may well be a wide overlap between the lower temperature varieties of quartz veins and the higher temperature varieties of sulphide bodies, depending on local conditions of concentration.

SPATIAL RELATIONSHIPS.

It may reasonably be assumed that the distance of a deposit from the parent magma is at least some measure of the difference in crystallization temperature between that deposit and the magma from which it originated. There are many difficulties in the way of an estimation of relative distances of such deposits from the original magma chamber. Many batholiths are not exposed; and deposits which on surface plan are far from plutonics may actually be very near, and directly above, the batholiths from which they originated. Again, the underground shape of an exposed batholith is significant in that connection, but it is not usually ascertained by underground work. In the case of the large batholiths, however, with clearcut exposed

edges, deductions may be drawn from the surface sections which are at least of some value in interpreting relative temperature conditions. It is to be noted that the more important sulphide bodies occur in the larger areas of volcanics, and that the small patches of volcanics, with two important exceptions, are not sulphide-bearing. The most extensive area of volcanics in the whole field—that which extends from west of the Flin Flon lake into the northeast arm of Athapapuskow lake—is also the most prolific in sulphide bodies. The second largest volcanic area, that north of Reed lake, also contains rather extensive sulphide bodies. It is a fair assumption that in the larger areas of volcanics, the distance from the main granite batholiths is greater than in the smaller bodies. The quartz veins, on the other hand, are disposed near the margins of the granite batholiths in Herb lake, Little Herb lake, Elbow lake, and Copper lake. As far as surface indications go, in the area as a whole, the sulphide bodies are further distant from the batholithic exposures than are the quartz veins. There are two instances however of very limited volcanic areas where rather extensive sulphide replacement is found. At Copper lake, in a small and somewhat isolated greenstone area, large pyrite-pyrrhotite replacements occur in close association with quartz veins carrying galena and gold, and at Tramping lake, in a narrow greenstone band, pyrrhotite-pyrite replacements of similar type to those of Copper lake are found near the granite contact. This would indicate a similarity of temperature conditions for the quartz-galena-gold type of veins and the pyrrhotite-pyrite sulphide bodies; and a measure of evidence for the point of view that there is a degree of overlap between the quartz veins and the sulphide bodies in the order of falling temperature. A further point in the spatial relations of the sulphide bodies has been noted by Bruce,[6] and may be of considerable significance. Where the sulphides are in fairly close relationship to granite, it is the smaller batholiths, or apophyses from the main granite masses, that have apparently given rise to the sulphide solutions. The Flin Flon and Mandy

[6] *Loc. cit.*, p. 63.

ore-bodies can best be explained in that way. In that way too could a differentiation take place most easily which would separate the sulphide solutions from the silica rich solutions, and cause the precipitation of certain of the sulphides at at least as high a temperature as some of the closely associated quartz veins.

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THE PYROPHYLLITE DEPOSITS OF THE DEEP RIVER REGION OF NORTH CAROLINA.[1]

J. L. STUCKEY.

INTRODUCTION.

THE pyrophyllite deposits of the Deep River region of North Carolina, are located in the central part of Moore and the south central part of Chatham Counties, the area described being about 5 miles wide and 20 miles long. It lies wholly within the Piedmont Plateau region, and the topographic features are characteristic of that province.

Although known for about 100 years, and worked more or less for 75 years, no detailed geologic work has been done on them. This is the more curious because of the unique character of the pyrophyllite, and the fact that these deposits are the only ones of commercial value known in the United States.

Scattered contributions relating to this and adjoining regions containing somewhat similar formations have, however, appeared[2] from time to time.

[1] Published by permission Director N. C. Geol. and Econ. Survey. Complete paper on file in Cornell University Library. Presented to the Society of Economic Geologists, May Meeting, 1924.

[2] For complete bibliography of the slate belt see:

Laney, F. B., "The Gold Hill Mining District," N. C. Geol. Surv. Bull. 21, 1910.

Pogue, J. E., Jr., "Cid Mining District of Davidson County," N. C. Geol. Surv. Bull. 22, 1910.

See also:

Olmstead, D., "Report on the Geology of North Carolina conducted under the Board of Agriculture," Raleigh, J. Gales and Son, 1825–'27.

Emmons, E., "Geological Report of the Midland Counties of North Carolina," Raleigh, Henry Turner, pp. 41 et seq., 1856.

Kerr, W. C., "Geology of North Carolina," Raleigh, 1875.

Williams, G. H., "The Distribution of Ancient Volcanic Rocks along the Eastern Border of North America," *Jour. Geol.*, vol. 2, pp. 1–31, 1894.

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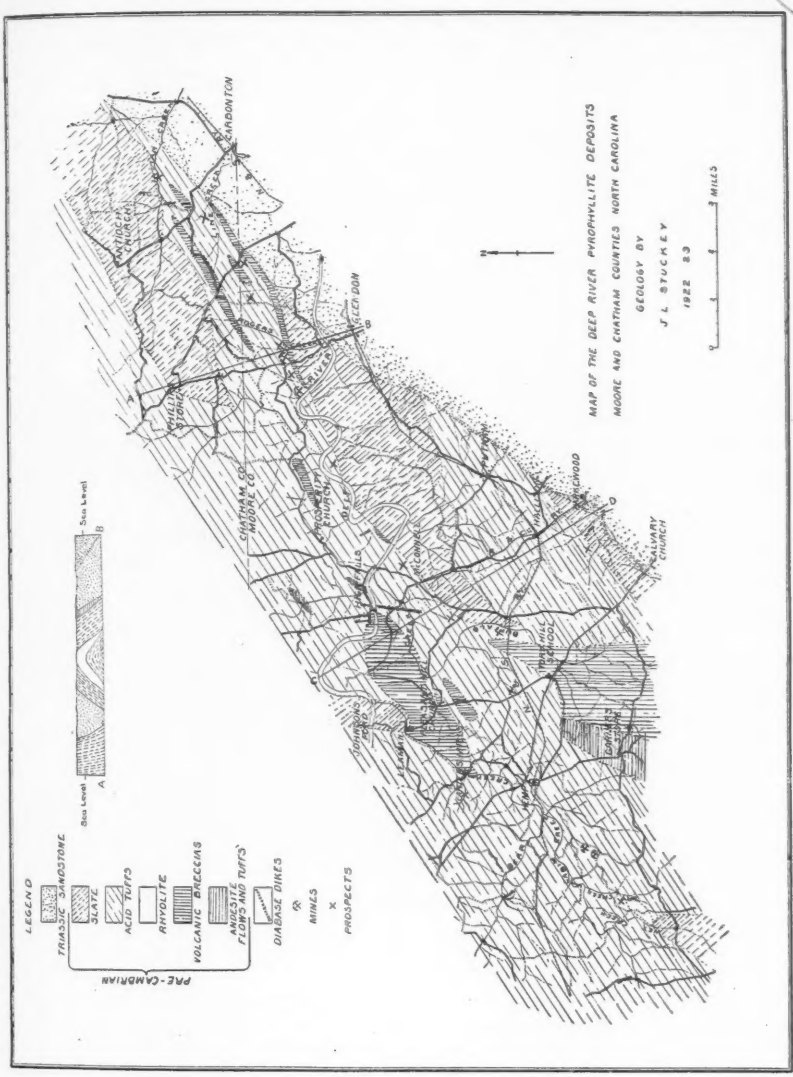

FIG. 1. Map of the Deep River Pyrophyllite Deposits.

GEOLOGY OF PYROPHYLLITE REGION.

The pyrophyllite deposits lie wholly within what is known as the "Carolina Slate Belt," although it is now recognized that the rocks are not all true slate, and that the name has been used because of the rather extensive development of cleavage in metamorphosed rocks of differing origin. The rock formations identified and mapped by the present writer (Fig. 1) include the following: (1) Slate; (2) Tuff of dacitic and rhyolitic character; (3) Rhyolite flow; (4) Volcanic breccia; (5) Andesite; (6) Diabase dikes.

Slate.—As shown on the map (Fig. 1) the slate occurs as elongated bands, separated by areas of volcanic rocks. It has a well developed cleavage, and in places still shows bedding, the presence of the latter indicating the position of existing folds. Along its margin the slate grades into a fine tuff. In fact the slate is a mixture of land waste and tuffaceous material, so that with an increase of the latter it grades into normal tuff.

Tuffs.—The tuffs, which have been classed and mapped as one formation (Fig. 1) because they are so intimately interbedded, consist of a fine acid tuff, and a coarse tuff.

Fine Tuff.—The fine acid tuff is confined to narrow bands and areas that are abundant in the slate and coarse tuff and grades into each of them. It shows practically every gradation from a massive silicious rock locally known as "gunflint" to a highly sheared material resembling a sericite schist, and in the more sheared varieties it often closely resembles a slate (Fig. 2).

Coarse Tuff.—The coarse tuff varies from a massive to a highly schistose rock, but occasionally has been so slightly changed as still to show some of its original character. There is also every gradation to a fine tuff on one hand and to an acid volcanic breccia on the other.

Nitze, H. B. C. and Hanna, G. B., "The Gold Deposits of North Carolina," N. C. Geol. Surv. Bull. 3, 1896.

Weed, W. H. and Watson, T. L., "The Virgilina Copper Deposits," ECON. GEOL., vol. I., pp. 309–330, 1906.

Laney, F. B., "The Geology and Ore Deposits of the Virgilina District of Virginia and North Carolina," N. C. Geol. Surv. Bull. 26, 1917.

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The fresh rock is made up of quartz and feldspar grains of less than ½ inch diameter set in a dense bluish or greenish gray ground mass, the whole often resembling an arkose.

Rhyolite.—Flows of rhyolite occur as narrow bands in the acid tuff, into which they grade. The rhyolite is dense and indistinctly porphyritic, and on fresh fracture has a greasy lustre. Flow lines have developed in numerous places, while amygdaloidal structure is also noticed.

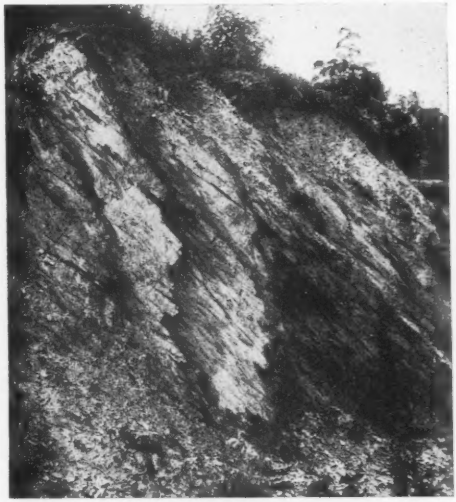

FIG. 2. Fine acid tuff, showing slaty cleavage, ¼ mile southwest of Hemp.

Volcanic Breccia.—This rock is widely scattered through the area mapped, occurring in long bands, lenses, or oval patches interbedded with the tuff. Three varieties are recognized: (1) acid volcanic breccia, (2) iron volcanic breccia, (3) basic volcanic breccia.

Acid Volcanic Breccia.—This rock consists partly of a brecciated tuff and partly of a brecciated rhyolite. The rock is con-

sidered a breccia when the fragments are abundant enough to attract attention as seen in the hand specimen and equal or exceed ½ inch in size.

When freshly broken the breccia has a greenish or mottled gray color produced by various colored fragments in a finer ground mass. In places the breccia has been strongly sheared and it always shows some mashing and schistosity, but on the whole is more massive than the finer tuff rocks.

Iron Breccia.—This rock has been so called because many of the fragments are so stained with iron oxide, chiefly hematite, as to cause the material to be mistaken for iron ore, and its weathered outcrops often resemble those of the diabase. The iron breccia is doubtless a variation of the acid breccia in which iron oxides, chiefly hematite are abundant. The name "iron breccia" has been used by both Emmons and Pratt and is retained here.

Basic Volcanic Breccia.—This rock apparently consists of andesitic tuffs and probably flows that have been brecciated. It ranges all the way from a fine and highly mashed tuff to a massive coarse breccia with fragments up to 4 inches in diameter. The andesitic type of breccia is far more abundant than the iron breccia.

Andesite.—Andesite is of limited occurrence within the area studied, only two small areas having been recognized (Fig. 1).

Diabase.—Diabase is widely though not abundantly distributed throughout the area mapped, and is found cutting all the formations described in this paper. It also cuts the Triassic sandstones to the east, consequently it is regarded as the youngest rock in the district.

Folding.—Though bedding planes are absent from most of the tuff rocks and only poorly preserved in the slate, there are some fairly conclusive proofs of folding. The well defined slaty cleavage and in places highly schistose character of the rocks, the distribution of the rock formations in long bands paralleling the strike, and the poorly preserved bedding planes in the slates, dipping at some points to the east and at others to the west, all indi-

cate that the rocks have been subjected to great pressure and some folding.

There are probably several possible interpretations of the structure in a region like this where details are hard to find, but the one that seems most reasonable to the writer is that of a synclinorium which has been closely compressed, so that the minor folds are steep on the western side of the synclinal troughs and flatten out to the east. The minor synclinal folds pinch from both ends towards the center and produce a canal or trough-like shape.

The slate seems to have consolidated and folded readily while the tuffs remained in a state of open texture and tended to mash and shear instead of folding. In the folding the slate in every case formed a syncline with the northwest side dipping steeply to the southeast, indicating a thrust movement from the southeast.

Schistosity.—The most evident and easily observed structural feature of the district is the prominent slaty cleavage or schistosity of the rocks (Fig. 2). This has a dip that is invariably to the northwest and varies from 45 to 85 degrees, while it strikes from north 60° east in the northeastern part of the district to north 20° east in the central and southwestern part.

The forces producing the main folding and schistosity had ceased long before the mineralization that produced the quartz veins and mineral deposits of the district as is shown by the fact that the quartz veins cut the schistosity.

Jointing.—Joint planes are abundant in all formations in the district and while they strike in every direction, the majority approximate a northeast-southwest or northwest-southeast direction. They are, however, most abundant in the massive rocks that apparently lie nearly horizontal, and are least abundant in the more schistose ones.

Faulting.—There is little direct evidence of faulting. In places a few minor displacements could be seen in old mines, but they seldom amounted to more than a few inches or a foot or two at most. It hardly seems probable that so much dynamic metamorphism could have taken place and such well defined cleavage

have developed without producing some faulting on a large scale, but conclusive proof is lacking.

The conclusions of earlier investigators of the gold and copper deposits of the slate belt and of the present investigation of the pyrophyllite deposits are that the mineral deposits of the region have been formed by hot solutions coming up from below and acting after the folding and development of schistosity of the rocks had taken place.

It is also interesting to note that the pyrophyllite deposits occur in a narrow zone of lenses not over 600 to 800 feet wide that can be traced along the strike for several miles. This line of pyrophyllite lenses is always found in the tuffaceous rocks and on the limbs of the anticlines as they were worked out and mapped in the field work.

It seems unreasonable for a special type of volcanic tuff to have been formed regularly over such great length and narrow width while at all other points there were such variations in the material. The conclusion, therefore, is that there was either faulting or some line of weakness developed, along which the solutions entered to form the mineral deposits.

Since no conclusive proof of faulting was found it was necessary to look to other causes for the line of weakness. The best cause for such a line of weakness seems to be a shear zone along the limbs of the folds, due either to drag movement in folding or to mashing and shearing in the tuffs instead of normal folding as took place in the slates.

In the pyrophyllite mines and prospects, though faults of greater magnitude than a few inches could not be proven, there is abundant proof of post-pyrophyllitic folding.

THE PYROPHYLLITE BODIES.

Introduction.—Just when pyrophyllite was first discovered in the Deep River Region is not known. Olmstead[3] in 1825 described the slate belt but did not mention the deposits. Em-

[3] Olmstead, D., "Report on the Geology of Noth Carolina," Raleigh, 1825–'27.

mons[4] in his report of 1856 gave a brief geological account of the deposits and the quarrying methods then used. Pratt[5] in 1900 described the deposits and published further analyses of the pyrophyllite. He pointed out that the deposits had been worked almost continuously since the Civil War. In 1913 Hafer[6] remarked that the pyrophyllite did not differ greatly from the sericite found in the old gold mines of the same belt and may have originated in the same manner. He also called attention to the masses of pyrite-bearing quartz that are often found associated with the pyrophyllite deposits.

Distribution.—Four mines, of sufficient importance to warrant the building of mills, and numerous prospects locally referred to as mines, represent the present pyrophyllite mining development in the Deep River region. These mines and prospects may be divided into two distinct zones or bands, both of which are found chiefly in the normal acid tuff. The more extensive of these zones begins on Indian Creek in Chatham County and extends southwest along an almost direct line of strike into Moore County about 10 miles, as far as the point where the Norfolk and Southern Railway crosses Buffalo Creek. The most important developments are about 1 mile north of Glendon.

The second zone lies about 2 miles southwest of Hemp along Cabin Creek, strikes N. 20° E. and can be traced along the strike from Carter's Mill on the northeast to Wet Creek on the southwest, a distance of about 4 miles. This zone contains a prominent body or lens of pyrophyllite, on which two mills have been built.

Another small body is known about 1½ miles southwest of Hallison near an old gold mine that lies near the contact between the tuff and slate.

Geologic Relations.—All the pyrophyllite bodies found in the

[4] Emmons, E., "Geological Report of the Midland Counties of North Carolina," pp. 52–54, Raleigh, 1856.

[5] Pratt, J. H., "Talc and Pyrophyllite in North Carolina," N. C. Geol. Surv. Econ. Paper 2, 1900.

[6] Hafer, C., "Pyrophyllite in North Carolina," *Eng. and Min. Jour.*, vol. 96, p. 623, 1913.

district are in the acid volcanic rocks, chiefly in the normal coarse-grained tuff, although they occur to a less extent with fine acid tuff and acid volcanic breccia. They were not found at any point in a basic or andesitic type of rock or associated with a typical water-laid slate of the district. Along the main pyrophyllite zone from Indian Creek to Deep River, especially at the important mines between Rogers Creek and the river, the southeastern or footwall side of the bodies, is an acid or iron volcanic breccia, and at places the pyrophyllite grades into and replaces parts of this rock. Near the point where the pyrophyllite formation is crossed by the Deep River north of Glendon there is locally a partial pyrophyllitization of the rhyolite on the northwest side of the zone. At the river the volcanic breccia on the footwall side disappears and is found only occasionally further to the southwest along the strike, but near Buffalo Creek is found on the hanging-wall side of the pyrophyllite bodies. In every other case the pyrophyllite on the hanging-wall side grades into normal acid tuff. Where the band of volcanic breccia is absent from the footwall side of the deposits the pyrophyllite bodies are much nearer the slate than those at Glendon, but they are never found in the normal slate.

The pyrophyllite area on Cabin Creek occurs in normal to coarse-grained acid tuff or breccia. Along the edges of the pyrophyllite bodies and between them along the strike near the Cagle gold mine there is much silicified fine tuff, but otherwise the country rock is a coarse to fine-grained acid volcanic tuff that is highly sheared and schistose.

Form and Structure.—A prominent feature of the pyrophyllite bodies is their irregular, oval, or lens-like form. They lie in a narrow band or zone aligned with the strike. Some of the largest are those at the Snow Mine on Rogers Creek, at the old Womble Mine north of Glendon, and at the McConnell Mine. The bodies vary in width from 200 to 500 feet, and in length parallel to the strike from 700 to 1,500 feet. Between these bodies there is often no surface indication of pyrophyllite.

The pyrophyllite area southwest of Hemp shows the same

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features. One important body 150 to 200 feet wide and about 2,000 feet long has been proven by prospecting and mining on Cabin Creek. Along the strike from either end of this body for some distance there is occasional evidence of other, but perhaps smaller, bodies.

The main zone along Deep River has a strike of from N. 40° to 60° E. and a cleavage dip of 30°–65° to the northwest, while in the area southwest of Hemp the strike varies from N. 20° E. to N. 40° E. and the cleavage dips from 45° to 85° to the northwest.

The different pyrophyllite bodies grade in both directions along the strike into acid tuff. Followed vertically downward there has been no change at the depths so far reached. Not only are they lenticular along the strike, but they also have an internal lenticular structure. In quarrying, lenses of pure pyrophyllite are found along with lenses of quartz, lenses of only partly replaced volcanic tuff and lenses of practically unaltered tuff.

That the pyrophyllite deposits have been intensely squeezed, crumpled and deformed is indicated by the numerous slickensided surfaces and variations in the strike and dip of the cleavage surfaces and planes of parting. Occasionally, as in the mine of the Standard Mineral Company near Hemp, there is limited faulting.

Mineralogy of the Deposits.—The minerals observed in the pyrophyllite deposits in the order of their abundance are pyrophyllite, quartz, chloritoid, sericite, pyrite, chlorite, feldspar, iron oxides, epidote, zircon, titanite, rutile, zeolites, and apatite. Of these only the first eight are present in important amounts. The other minerals are noticed in but small quantities, to the extent they might occur as accessory constituents of an igneous rock or as products of regional metamorphism or weathering.

Pyrophyllite varies in color from nearly black through yellowish white, green, and apple green to pure white, has a specific gravity of about 2.8 to 2.9 and a hardness less than the finger nail. It occurs in masses, lenses, and pockets associated with chloritoid, sericite, pyrite, and iron oxides, has a greasy feel, pearly luster and a foliated structure.

Quartz is abundant everywhere except in the very best grade

of pyrophyllite. It occurs: (1) as large masses of a cherty or milky appearance; (2) as clear veins and stringers in the deposits and along the walls and; (3) as small masses and nodules in the altered or only partly altered rock.

Chloritoid is found in small amounts in all the pyrophyllite deposits, most abundantly in those north of Glendon where they lie in contact with the "iron volcanic breccia." It varies from brown to dark green in color, the latter being far more common. In thin section it is seen to form sheaf-like patches made up of bladed crystals that are often twinned and do not have well developed crystal ends (Plate I., Fig. 4).

Sericite [7] is present in varying amounts disseminated through the impure pyrophyllite in small scales and flakes. At places it occurs in pockets and lenses near the bottom of the mine as a massive compact material.

Pyrite is present in small amounts associated with the silicified tuff along the walls of the pyrophyllite bodies and in the included lenses of silicified country rock.

Chlorite occurs commonly in the impure portions of the pyrophyllite bodies and often in otherwise pure pyrophyllite.

Feldspars, as orthoclase and albite and in one case andesine, were found in small amounts in the less silicified portions of the wall rock.

Iron oxides, chiefly hematite and magnetite are found in small amounts in each pyrophyllite deposit studied but most abundantly in the footwall of the mine near Glendon which is chiefly iron breccia.

Petrography.—A careful study of about 75 thin sections cut from the various mines and quarries shows that the pyrophyllite deposits have been formed in a normal volcanic tuff and to some extent in a volcanic breccia that varied from dacitic to rhyolitic in composition.

Sections from specimens of tuff collected along the walls and

[7] In the material studied for the preparation of this paper sericite has been distinguished from pyrophyllite by its smaller optical angle and by the presence of potash in the chemical analyses.

edges of the pyrophyllite bodies usually show as a first change marked silicification accompanied by a marked decrease in the feldspar content. In some places as at the Standard Mineral Company's Mine, near Hemp, and the Snow prospect on Rogers Creek, silicification seems to have been followed immediately by the development of pyrophyllite. In the Womble Mine and the mine of Southern Talc Company, near Glendon, the silicification seems to have been accompanied by the development of pyrite as this mineral is sometimes found in the silicified wall rock but seldom in the pyrophyllite, while on the foot wall side of the Womble Mine there was a remarkable development of chloritoid along with or more probably immediately after the major silicification.

In passing from the walls of the deposits into the mineral bodies themselves there is a decrease in the amount of quartz, pyrite, and chloritoid. The best mineral bodies consist of practically pure pyrophyllite or pyrophyllite and a small amount of sericite interlensed with lenses of quartz and partly altered country rock.

The chief minerals, pyrophyllite, quartz, chloritoid, sericite, pyrite, feldspar, iron oxides, and chlorite have definite relations to each other.

There is a close relation between the chloritoid and the iron oxides, for the former is far more abundant in the deposits where the latter is present, in fact it shows a marked local concentration in that part of any deposit where iron oxides are most abundant.

The Womble Mine at Glendon has a typical iron breccia for its foot wall, in which the iron consists largely of hematite and magnetite. In this mine chloritoid is present in abundance and it is concentrated largely on the foot wall side near the iron breccia. Thin sections from such specimens show that the chloritoid is in direct contact and association with small amounts of magnetite and hematite. The chloritoid was not observed replacing the iron oxides, but the marked increase and close association of chloritoid with the iron oxides at every point where the latter are present suggest a close genetic relation between the two.

The chloritoid was developed along with or soon after the silicification of the tuff and in thin sections it is seen to have partially replaced the quartz (Plate I., Fig. 4).

The pyrophyllite appears to have been later than the chloritoid. Some sections showing an abundance of chloritoid contain no pyrophyllite or only tiny flakes of it. This indicates that the chloritoid is earlier than the pyrophyllite in these sections. But in practically every section where chloritoid is abundant pyrophyllite is also abundant. Where pyrophyllite is present in the section with chloritoid it occurs in every crack and opening in the sheaves and bundles of chloritoid, and intergrown into the broken ends of the crystals and even along the cleavage cracks seemingly indicating definite replacement.

The microscope shows the pyrophyllite to be the last mineral formed. In every case silicification had taken place before the development of pyrophyllite. The feldspars disappeared with the silicification so that feldspar and pyrophyllite are seldom found in the same section. Practically every section that contains pyrophyllite contains some quartz, the amount of the latter depending on the purity of the specimen in terms of pyrophyllite. In every one of these sections the pyrophyllite is replacing the quartz (Plate I., Fig. 5). This is true of the wall rock, of the masses of cherty or milky quartz in the pyrophyllite, and of the clear quartz seams and veins that cut the pyrophyllite at various angles.

The sericite occurs closely associated with the pyrophyllite. Thin sections cut from partly silicified, partly pyrophyllitized masses along the foot walls and in the deposits show a small amount of sericite occurring with the pyrophyllite and showing about the same relations to the quartz. The cherty or flinty masses of quartz in the pyrophyllite are cracked and shattered, and along these cracks pyrophyllite and some sericite are found replacing the quartz.

ORIGIN OF THE PYROPHYLLITE BODIES.

In considering the origin of the pyrophyllite bodies, their relation to each other and the enclosing rocks, their shape and dis-

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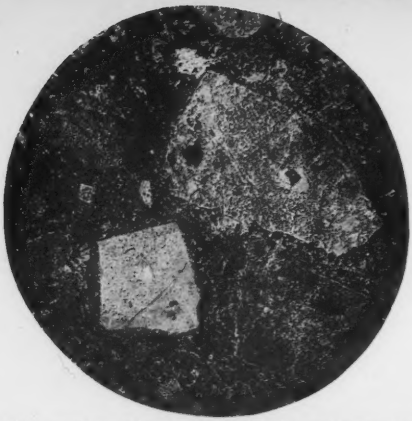


FIG. 3. Thin section of coarse acid tuff, ordinary light, × 40.

FIG. 4. Thin section showing chloritoid replacing quartz, crossed nicols, × 64.

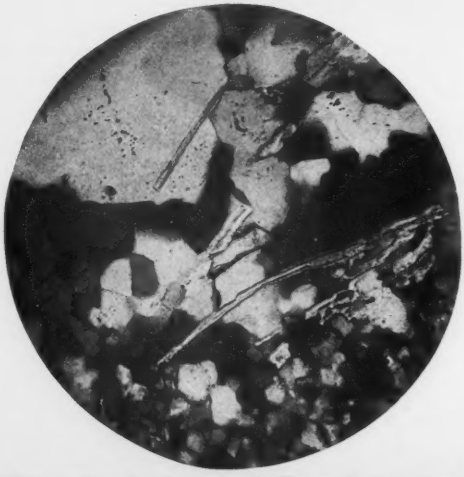


FIG. 5. Thin section showing pyrophyllite replacing quartz, crossed nicols, × 100.

FIG. 6. Mashed and folded pyrophyllite one mile north of Glendon.

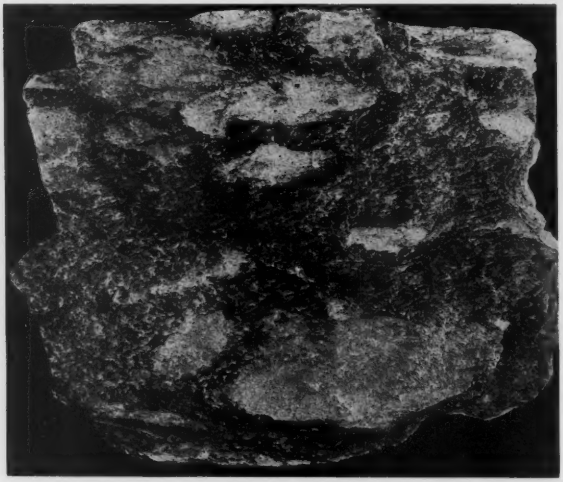
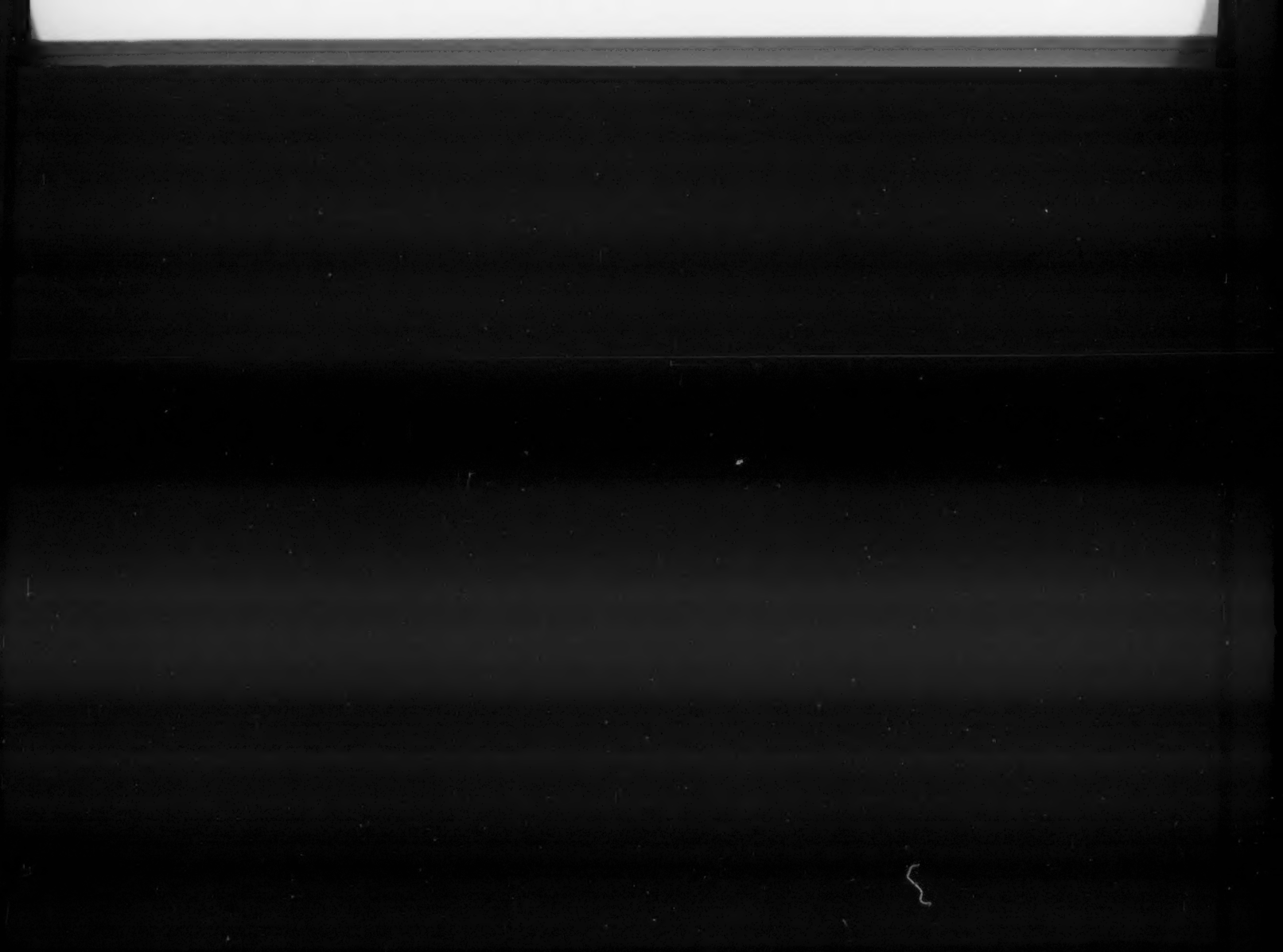


FIG. 7. Hand specimen of acid volcanic breccia, replaced by pyrophyllite.



tribution, their mineralogical composition and the relation of the constituent minerals to each other, have been taken into account. Future developments of the deposits may bring forth additional facts that may call for other theories and explanations than those here set forth. One great difficulty in formulating a theory of origin is the complex nature and highly metamorphosed state of the rocks of the "slate belt."

Earlier Theories.—Before discussing the origin of the North Carolina pyrophyllite reference may be made to the views already expressed by other writers on the origin of this mineral and the chloritoid and sericite associated with it.

Emmons [8] (1856) considered pyrophyllite (agalmatolite) as a sedimentary rock near the base of his Taconic system. Levy [9] and Lacroix (1888) state that pyrophyllite occurs in metamorphic rocks while Dana [10] (1909) classed it as a mineral forming at the base of schists or as a mineral of the crystalling schists and Paleozoic metamorphics. Clapp [11] (1913) assumed that alunite and pyrophyllite are probably developed only under conditions of moderate temperature and pressure such as exist near the surface. Buddington [12] concluded that the pyrophyllite and pinite of the Avondale volcanics were formed by metasomatic replacement of silicified rhyolites or rhyolitic volcanics by hot waters under conditions of intermediate temperature and pressure. LeChatelier [13] determined the temperature at which pyrophyllite loses its water and found two points of marked loss, one at 700° and the other

[8] Emmons, E., "Geological Report of the Midland Counties of North Carolina," Raleigh, 1856.

[9] Levy, M. and Lacroix, A., "Mineraux des Roches," p. 254, 1888.

[10] Dana, E. S., "A System of Mineralogy," p. 691, 1909.

[11] Clapp, C. H., "The Geology of the Alunite and Pyrophyllite Rocks of Kyuquot Sound, Vancouver Island," Summary Report of the Geol. Survey, Dept. of Mines for 1913, pp. 109–126, 1914.

[12] Buddington, A. F., "Pyrophyllitization, Pinitization, and Silicification of Rocks around Conception Bay, Newfoundland," *Jour. of Geol.*, vol. 24, pp. 130–152. 1916.

[13] LeChatelier, M. H., "De l'Action de la Chaleur sur les Argiles," Bull. Soc. Min. France, 10, p. 207, 1887.

at 850° C. The present writer [14] made a comparative dehydration test of pyrophyllite and sericite and found that sericite lost its water much faster than pyrophyllite at lower temperatures and at 750° C. was practically dehydrated while the pyrophyllite still held about 1 per cent. water.

Sericite is classed by Rogers [15] as a typically low temperature mineral associated with the last stages of hydrothermal alteration, while Lindgren [16] classes it as a mineral common to hydrothermal alteration at shallow and intermediate depths and points out that in acid rocks of the rhyolitic type silicification and sericitization are common near the surface, but does not agree with Rogers [17] that sericite is a late mineral.

While much has been published regarding the nature of chloritoid there is little definite information on its genesis. Clark [18] states that chloritoid is formed in schists where much iron and water are present, and that it is intermediate between the micas and chlorite and may alter into either. Manasse [19] describes a schist of sericite, quartz, rutile, tourmaline, chlorite, and epidote, from the Alps of Italy, closely associated with and occurring on both sides of a marble, in which chloritoid is abundant.

Niggli [20] in a study of the chloritoid and ottrelite groups of the Swiss Alps decided that the two minerals are identical. He pointed out that the chloritoid is abundantly developed in schists that were originally high in clay content and believes that its formation was directly due to pressure and relatively independent of temperature. He gives a diagram showing that regardless of

[14] Stuckey, J. L., "The Dehydration Temperature of Pyrophyllite and Sericite," *Jour. Amer. Ceramic Soc.*, vol. 7, pp. 235–237, 1924.

[15] Rogers, A. F., "Sericite as a Low Temperature Hydrothermal Mineral," ECON. GEOL., vol. 11, pp. 118–150, 1916.

[16] Lindgren, W., "Mineral Deposits," pp. 478–480 and 549–564, 1919.

[17] *Op. cit.*

[18] Clarke, F. W., "Data of Geochemistry," U. S. G. S. Bull. 695, pp. 615–616, 1920.

[19] Manasse, E., "Cloritoide (Ottrelite) delle Alpi Apuane," *Mem. Soc. Tosc.*, vol. 26, pp. 121–142, 1910.

[20] Niggli, P., "Die chloritoidschiefer und die sedementaren Zone am Nordstrande des Gottardmassives," *Beitrage zur Geologischen Karte der Schweiz*, vol. 36, 1912.

temperature chloritoid is formed with an increase in pressure and conversely it drops out when the pressure is diminished.

Analyses of Rocks.—In the following table there are a number of chemical analyses of rocks and minerals from the Deep River region and for comparison some similar rocks from other regions. Number 1 is a normal dacite tuff from near Monteith Bay on Vancouver Island. Number 2 is the same type of rock a short distance away altered to quartz and sericite. Number 3 is a dacite tuff from near Gold Hill, North Carolina, and Number 4 from nearby is the same kind of rock after silicification.

	1*	2*	3†	4†	5	6	7	8	9
SiO_2	73.22	87.80	56.94	72.16	68.40	57.58	64.68	29.28	47.07
Al_2O_3	13.46	9.08	20.96	9.00	23.80	33.31	28.34	37.98	36.89
Fe_2O_3	2.33	0.40	3.97	2.47	0.38	0.33	0.60	2.32	.42
FeO	0.96	nd		3.30	nd	nd	nd	21.97	nd
MgO	0.42		0.41	3.03	0.16	trace	trace	1.28	0.20
CaO	1.50		6.01	0.43	0.51	trace	0.72	trace	0.55
Na_2O	5.46	0.62	3.96	3.69	0.07	0.06	0.38	nd	1.34
K_2O	1.74	1.70	1.29	0.24	1.48	3.90	0.01	nd	8.21
H_2O	0.62	1.04	0.19	4.08	4.96	5.56	5.54	6.04	5.05
TiO_2	0.28	nd			nd	nd	nd	0.86	trace
MnO	0.10				nd	nd	trace	0.29	nd
CO_2			2.52						
S		trace		1.85					
	100.09	100.04	96.25	100.25	99.76	100.74	100.27	100.02	99.73

1. Dacite tuff, 1 mile southeast of Monteith Bay, N. L. Turner, analyst.
2. Cherty quartz-sericite rock, Quarry of British Columbia Pottery Company, Monteith claim.
3. Typical coarse tuff near Morgan's Mill, Gold Hill, A. S. Wheeler, analyst.
4. Tuff, more or less silicified, Union Mine, A. S. Wheeer, analyst.
5. Silicified tuff, partially pyrophyllized, Standard Mineral Company's Mine, J. L. Stuckey, analyst.
6. Pyrophyllite, Standard Mineral Company's Mine, J. L. Stuckey, analyst.
7. Pyrophyllite, Womble Mine, J. L. Stuckey, analyst.
8. Chloritoid, Womble Mine, J. L. Stuckey, analyst.
9. Sericite, Standard Mineral Company's Mine, J. L. Stuckey, analyst.

* Clapp, C. H., "The Geology of the Alunite and Pyrophyllite Rocks of Kyuquot Sound, Vancouver Island," Summary Rept. of the Geol. Surv., Dept. of Mines for 1913, pp. 109–126.

† Laney, F. B., "The Gold Hill Mining District," N. C. Geol. and Econ. Surv. Bull. 21, p. 41, 1910.

The material for analyses 3 and 4 came from the same "slate belt" of which the Deep River region is a part. Both these analyses show a decrease in alumina and in alkalies as the silica increases. The same conditions hold in the deposits around Conception Bay described by Buddington. Further replacement by pyrophyllite or sericite is accompanied by an increase in alumina, potash increasing with the sericite content.

While no chemical analyses were made of any tuffs of the Deep River district, a study of thin sections indicated that the same things happen there. The normal tuff consists largely of acid feldspars and quartz. The silicified rocks from the mineral bodies show quartz and a very small amount of feldspars as the chief minerals. This seems to indicate a decrease in the alumina and alkalies. Analyses 5, 6, and 7 represent pyrophyllite of different grades of purity, and indicating varying amounts of admixed sericite, while 8 and 9 represent chloritoid and sericite respectively. Analysis 5 is a silicious material that would seem to contain both pyrophyllite and sericite. Number 6 is free from grit or quartz but evidently contains considerable sericite, while number 7 is practically a pure pyrophyllite.

Origin of North Carolina Pyrophyllite.—The field, microscopic, and chemical evidence suggest that the pyrophyllite bodies have been formed through metasomatic replacement of acid tuffs and breccias of both dacitic and rhyolitic composition. Evidences that the deposits have been formed by replacement are as follows: (1) gradational contacts between pure pyrophyllite and the unaltered country rock; (2) the preservation of structures of the primary rocks in the mineralized rocks, such as bedding planes of the finer tuffs, and fragmental outlines of the volcanic breccia (Plate II., Fig. 7); (3) the presence of masses and lenses of the country rock practically pure or only partly altered, apparently unattached and completely surrounded in the mineral bodies; (4) the introduction of certain elements and the removal of others; (5) the lack of any noticeable change in volume of the original rocks during the process; and (6) the massive and

homogeneous structure of the pyrophyllite which has not been observed in crystals in any of the bodies.

The following sequence of events is deduced: (1) Metamorphism of the volcanic tuffs and flows in which the mineral bodies were later formed.

(2) The silicification of the tuffs and breccias by metasomatic processes as is indicated by the presence of original structure of the volcanics in the silicified material, and by the presence of entirely surrounded fragments of only partly silicified tuff in the quartz areas.

(3) Accompanying or immediately following the silicification came the development of pyrite in the silicified areas.

(4) Development of chloritoid to some extent in all the mineral bodies and in abundance in parts of those bodies that are near the masses of iron breccia.

(5) Development of pyrophyllite by replacement of the previously silicified and mineralized tuff.

(6) Development of the sericite closely associated with or immediately following the pyrophyllite.

Source of the Solutions.—That the mineral bodies were formed by heated solutions coming up from below seems established from the foregoing description of the distribution, petrography, and chemical composition of the mineral deposits. However, a source for such solutions has not been established. No igneous rocks were found exposed at the surface, other than the diabase dikes which are later than the mineralization, either in the area mapped or within any reasonable distance of the area.

There were for a number of years numerous active gold and copper mines throughout the slate belt that were important enough to receive quite a little attention in reports of the State Geological Survey from 1885 to 1898. Four of these mines are found in the district covered in this paper. Nitze [21] and Hanna in 1896 pointed out that the gold and copper deposits throughout the entire slate belt were very similar and that much silicification

[21] Nitze, H. B. C. and Hanna, G. B., "Gold Deposits of North Carolina," N. C. Geol. Surv. Bull. 3, pp. 44–49, 1896.

had accompanied the formation of the ores. They attributed the mineralization to hot carbonated, alkaline waters. Laney [22] found much silicification associated with the ore bodies at Gold Hill. He concluded that the mineralization had been produced by hot solutions given off from a granite that had been intruded into the slates in the immediate neighborhood of the ore bodies. Pogue [23] found practically the same conditions in the Cid district of Davidson County except that there were no known intrusive igneous rocks to have furnished the solutions. He concluded, however, that there were large igneous masses intruded into the rocks of the district from below, but that these rocks did not reach the surface.

If Nitze and Hanna are right in their statement that the gold and copper mines of the whole slate belt are in general alike, and if Pogue is right in assuming a large intrusive magma below the Cid district which belonged to a period when large amounts of igneous rocks were intruded into the Piedmont Plateau and brought near the surface, it seems that the same conditions must have existed in the Deep River region and that the gold ores of the Cagle and other mines were formed by hot solutions from igneous magmas below. There is a close relation between the pyrophyllite bodies and the metalliferous deposits. It seems that the same source that furnished the hot solutions to deposit the gold and copper also furnished the hot solutions to produce the pyrophyllite bodies.

Conditions of Pyrophyllite Formation.—Different investigators have agreed that pyrophyllite may form at conditions varying from high temperature and pressure to low temperature and pressure such as exist near the surface.

The information available as to the formation of chloritoid seems to indicate that it forms at fairly high temperature and according to Niggli is directly dependent on fairly high pressure.

[22] Laney, F. B., "The Gold Hill Mining District," N. C. Geol. Surv. Bull. 21, pp. 96–98, 1910.

[23] Pogue, J. E., Jr., "The Cid Mining District of Davidson County," N. C. Geol. Surv. Bull. 22, pp. 124–128, 1910.

Pogue [24] and Laney [25] have both indicated that the gold and copper areas of the district were formed under conditions of temperature and pressure varying from high to intermediate. That the pyrophyllite bodies were formed by hot solutions given off from the same source and acting at about the same time is indicated by the close association of the pyrophyllite bodies with the old gold mines especially the Cagle gold mine in the Deep River region and at the Brewer [26] gold mine in South Carolina, and Hafer [27] noted the presence of copper bearing pyrite in the mine of the Southern Talc company at Glendon.

It is possible that in the Deep River region there was a gradual change from high temperature and pressure to the low temperature and pressure of hydro-thermal alteration near the surface during the period of activity of the hot solution. The writer, however, agrees with Buddington [28] and believes that the pyrophyllite deposits of the Deep River region were formed under conditions of intermediate temperatures and pressure.

OPERATIONS AND SUPPLY.

The pyrophyllite mining so far carried on in the district has been by shallow pits and open cuts, the greatest depth reached being 125 feet in the mine of the Standard Mineral Company near Hemp. In none of the mines or prospects has any difference been found in the pyrophyllite or associated minerals with depth. Pratt [29] has pointed out that the pyrophyllite formation

[24] *Op. cit.*, p. 127.

[25] Laney, F. B., "The Geology and Ore Deposits of the Virgilina District of Virginia and North Carolina," N. C. Geol. Surv. Bull. 26, 1917.

[26] Powers, F. D., "The Pambula Gold Deposits," *Quart. Jour. Geol. Soc.*, vol. 49, pp. 233–235, 1893. Bauerman, H., Statement at the end of Power's paper.

[27] Hafer, Claud, "Pyrophyllite in North Carolina," *Eng. and Min. Jour.*, vol. 96, p. 603, 1913.

[28] Buddington, A. F., "Pyrophyllitization, Pinitization, and Silicification of Rocks around Conception Bay, Newfoundland," *Jour. Geol.*, vol. 24, pp. 130–152, 1916.

[29] Pratt, J. H., "Talc and Pyrophyllite Deposits in North Carolina," N. C. Geol. Surv. Econ. Paper 3, 1900.

is continuous and of considerable depth. Hafer [30] suggested that pyrophyllite should be found to the same depth that the gold mines of the area have reached and also pointed out that gold had been mined to a depth of 800 feet. The result of the present investigation coupled with the close relationship of the pyrophyllite to old gold mines in parts of the area leads to the conclusion that one may expect to find pyrophyllite in paying amounts to a minimum depth of 500 feet.

The milling practice has been such that only material pure enough to make a good finished product went into the mill. This has meant a large waste of material that contains 50 to 75 per cent. of pyrophyllite. If the deposits extend to a depth of 500 feet or more and all material of 60 per cent. purity could be used it means a tremendous tonnage of pyrophyllite.

Ladoo [31] referring to the Glendon deposits says there is enough material to supply a good sized mill for several years. The deposit at Hemp is equally promising. The conclusion is, therefore, that there is enough pyrophyllite in the Deep River region to supply a fairly large industry for years.

USES OF PYROPHYLLITE.

The uses of pyrophyllite have expanded with the development of mining in the Deep River region. It was first used for grave stones, chimneys, fire places, and stove linings. As early as 1856 Emmons [32] pointed out that besides its local uses pyrophyllite was a good substitute for chalk, and as a base in cosmetics.

Below is given as complete a list of uses [33] of the pyrophyllite from the Deep River region of North Carolina as it was possible to obtain: roofing paper manufacture; cotton cordage; textile

[30] Hafer, C., "Pyrophyllite in North Carolina," Eng. and Min. Jour., vol. 96, p. 623, 1913.

[31] Ladoo, R. B., "Talc and Soapstone, their Mining, Milling, Products, and Uses," Bureau of Mines Bull. 213, pp. 118–121, 1923.

[32] Emmons, E., "Geology of the Midland Counties of North Carolina," pp. 52–54, 1856.

[33] Ladoo, R. B., "Talc and Soapstone, their Mining, Milling, Products, and Uses," Bureau of Mines Bull. 213, 1923.

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manufacture; paper industry; rubber manufacture; soap manufacture; pipe covering compounds; pottery and porcelain; asbestos industry; paint manufacture; toilet preparations; bleaching industries; crayons and pencils; and sheet asphalt.

The writer takes pleasure in acknowledging the assistance given him by Profs. A. C. Gill and H. Ries during the course of the work, and also to Dr. J. H. Pratt, former Director of the North Carolina Geological Survey, for facilities offered in carrying on the field work.

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GEOLOGY AND THE LOCATION OF DAMS ON THE CANADIAN RIVER, TEXAS.[1]

LEROY T. PATTON.

In a former article[2] the writer discussed the relation of geology to the location of dams on certain rivers of West Texas. That article did not include a description of the geologic conditions of the Canadian River valley, which was also investigated at the time the other surveys were made.

Topography.—The Canadian River throughout practically the whole of its course across the Texas Panhandle flows in a deep valley, which has been excavated in the High Plains. This valley from rim to rim attains a width of 25 miles. Within the greater valley a narrow, steep-sided canyon has been cut, which, in places, has a depth of 300 or more feet. The depth of the greater valley, measured from rim rock to the to the bottom of the inner canyon, reaches 800 feet.

North of the Canadian River the great debris apron, which constitutes the surface formation of the Panhandle of Texas, is known as the High Plains; south of the Canadian it is known as the Llano Estacado. As these names are used for divisions of the larger physiographic province known as the High Plains, the latter will be used to indicate that part of the province which lies in Texas.

The topography of the High Plains is an almost level plain, which has a slope to the east of approximately 10 feet to the mile. Few drainage lines have been developed on the surface of this plain, as much of the water which falls on the surface sinks into the ground and is removed by underground drainage through the sand and gravel deposits below. The plain is,

[1] Published by permission of the Texas State Board of Water Engineers.

[2] Patton, L. T., "Geology and the Location of Dams in West Texas," *Jour. Economic Geology*, vol. 19, No. 8, 1924.

therefore, dissected by few stream valleys except those of through-flowing rivers like that of the Canadian.

Formations.—The debris apron of which the High Plains is composed consists of unconsolidated sand, gravel, and some consolidated material such as the so-called "mortar-beds." These are beds of sand and gravel that have become more or less firmly cemented, with occasional sandstones and limestones, and are Tertiary and Quaternary in age. Near the top occurs a secondary deposit usually known as a caliche, a white chalky limestone of varying thickness, averaging two or three feet. This outcrops along the rim of the greater valley of the Canadian and other valleys and is locally known as the "rim rock."

The surface of the High Plains is covered by a mantle of loess-like soil. Where sufficient moisture is available this soil makes excellent farming land.

Underlying the debris apron described above are Permian and Triassic rocks. The Permian deposits, so far as observed in the Canadian River valley, belong to the upper part of the Double Mountain formation. They consist of brick red shales and sandstones, the latter containing a conspicuous amount of silty material, gypsum, and some dolomite. The upper two hundred feet exposed contains much less gypsum than the part below. Resting unconformably upon the Permian beds are the Triassic beds. The lower part of the Triassic formation in the Canadian River valley consists of shale more than two hundred feet in thickness. Above these shale beds are coarse sandstone and conglomerate. These vary somewhat in different places, but in the main consist of one or more bands of sandstone three to four feet in thickness separated by intervals of shale.

At least a portion of the Canadian River Valley was cut before the deposition of the sands and gravels of the debris apron of the High Plains, since areas are found within the valley from which parts or all of the Triassic beds have been removed and the later deposits rest unconformably upon the eroded surfaces. It thus happens that these deposits are found at different

places within the valley, instead of occupying only the rim and upper portion of the sides of the greater valley, as would be the case had the cutting of the valley taken place subsequent to their deposition. This is important in considering the question of location of dams on the river, since in some cases the sides of the inner canyon are composed of these later sediments.

Nature of the River.—The nature of the Canadian River itself deserves special attention. At most seasons of the year it contains but little water, flowing in many distributing channels, and does little work of erosion. At times of flood, however, it carries a large volume of water and is a formidable stream. Then it deepens its channel in the swifter part, while at the sides, where the current is not so strong, deposition takes place. After the flood has subsided the feebler currents deposit material where the current had been eroding during the flood, and the deepened channel is filled. In this way thick deposits of so-called quicksand are formed in the river bed.

Dam Locations.—The Canadian is locally supposed to be a stream which has everywhere great depths of quicksand, that would present difficulties in the construction of dams. Though it is no doubt true that there are many places where considerable depths of quicksand will be encountered, there are certain geological conditions which would tend to prevent the accumulation of much quicksand at other places.

In the western part of the Panhandle the river cuts through several large structural domes; consequently there are a number of places where the river crosses strata that resist erosion. Of such strata the most important is a hard dolomite bed belonging to the upper part of the Permian. This member, which has been given the name of Alibates dolomite, consists of two bands of dolomite, each from four to eight feet in thickness, separated by a thin bed of shale; in some places they merge together.

Where such hard and resistant strata occur it is not to be expected that the scour and fill method of erosion described above would be effective in temporarily deepening the channel of the

river, and it is therefore improbable that excessive depths of sand would be found at such places. It is believed that due regard to geologic conditions would indicate the sites that would best warrant further investigation by soundings.

An illustration of this control of geologic conditions over the accumulation of sand in the river bottom is seen just north of Amarillo, where the Colorado and Gulf Highway bridge crosses the Canadian River. The piers of this bridge rest on solid rock which was struck at the depth of a few feet, and, so far as the writer was able to obtain information about the construction of the bridge, the evidence indicates that the rock bottom is continuous across the river at this place.

In certain places, as for instance where the river crosses the side of the large John Ray dome, it penetrates deeply into the Permian strata and heavy beds of gypsum appear in the sides of the canyon. In such situations the resistant Alibates dolomite forms the rim of the inner canyon and so permits the formation of a narrow steep-sided canyon. An example is seen in Section 60, Block 47, H. & T. C. R. R., Section 105 Block 46, H. & T. C. R. R., Potter Co. The canyon here is less than one half mile wide and 325 feet deep. Near the bottom of the canyon, however, the massive gypsum appears.

West of the central part of Potter County, Triassic formations may be found in the inner canyon walls in situations where the structural conditions have brought the Permian formations to the level of the river. The Triassic formations offer favorable geologic conditions for the location of dams, since they contain no gypsum beds. They are not as resistant to erosion as the Alibates dolomite, however, and so do not form as favorable topographic sites as where the dolomite caps the canyon rim. Places may be found, however, where dams of reasonable height might be constructed with the upper part of the Permian as a base and the Traissic beds at the side. From the geological standpoint such sites would be excellent, especially where the Alibates dolomite is present in the upper part of the

Permian. Under such conditions little quicksand should be expected; an excellent foundation for the dam would be offered; there would be no danger on account of the presence of gypsum; and there would not be an undue loss of water by seepage.

As was mentioned in the earlier part of the paper, there was erosion before the deposition of the Tertiary and Quaternary deposits, and the latter deposits are therefore laid down unconformably upon both the Triassic and Permian formations. Situations may be found, therefore, where these deposits form the sides of the inner canyon and rest either upon the top of the Permian or upon some part of the Triassic. Where these deposits consist of loose, unconsolidated sand and gravel both topography and geology are unfavorable for the location of dams. Where sand and gravel are consolidated, the conditions are more favorable, and localities where there is 75 to 100 feet of consolidated sand and gravel are known. Where such a deposit forms the sides of the canyon, and if there is little quicksand and a good foundation, then fairly favorable conditions for dam locations exist, though not so favorable as where Triassic formations occupy similar positions.

SUMMARY.

In summing up the data concerning the Canadian River valley it may be said:

1. That from the engineering standpoint it would be desirable to obtain a location as far to the west as possible.

2. That the popular supposition that no dam site on the Canadian River is feasible on account of quicksand is unjustified; it is probable that a number of sites might be found, where this difficulty would not be enountered, if due regard is given to the geologic conditions; and that no site which offers favorable conditions otherwise should be condemned on this score without careful sounding of the river at that place.

3. That combinations of geologic and structural conditions

creating more or less favorable sites for the location of dams may be found.

4. That these combinations are found to a greater extent in the western than in the eastern part of the Panhandle, thus meeting the engineering demands, which necessitate the location of a dam as far west as possible.

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THE MECHANISM OF REPLACEMENT AND RECRYSTALLIZATION.

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THE attention of geological workers, especially those who use the microscope as a valuable aid in the solution of geological problems, has been directed to the fact that a tendency exists toward overconfidence in the interpretation of microscopic structures. Such confidence is shown regardless of the fact that workers in the sister science of metallography have found that it is often impossible to interpret correctly microscopic structures without additional lines of research, such as thermal study, accompanying the microscopic evidence. While the experience of the metallographer teaches caution, his science also serves as a source of much information that has direct application to problems such as are encountered in the study of polished ore sections. It is the purpose of this paper to review some of the late developments of the science of metallography and show their application to the geological problems presented by replacement and recrystallization phenomena.

The intercrystalline cement hypothesis [1] advances the idea that the crystallization of material takes place by the addition of crystal units containing large numbers of atoms. In the region where two crystals abut against one another—that is, at the grain boundaries—there would have to be some material which could not attach itself to either crystal because of being too small in amount to form crystal units. Since the crystalline grains have different orientations, the units or blocks of one would not fit in with the blocks of the other, and interstices of irregular shape would be left which could not be filled up with other crys-

[1] The statement of this hypothesis is taken from "The Science of Metals" by Jeffries and Archer, N. Y., 1924, pp. 72–3.

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tals no matter what their orientation. The material remaining in these interstices must then retain the structure of the liquid—*i.e.*, must be amorphous.

This conception is no longer tenable, inasmuch as it now appears quite certain that the "crystal units" consist of one atom each. The actual conditions must nevertheless be very similar, in a qualitative way and on a smaller scale, to those represented by this hypothesis. Certainly, where two crystals of different orientations meet, it is not geometrically possible for all the atoms present to have places in an undisturbed space lattice without leaving some voids.

There are three possible conditions: (1) There are voids between the two crystals; (2) there is a zone in which some of the atoms are held in both crystal lattices, in which case the lattices would be distorted at the surface of contact; or (3) there is a zone of disorganized or *amorphous* material. The hypothesis that amorphous cement exists in the interstices offers satisfactory explanation of many phenomena observed such as certain deformational and strength properties of metals and furnishes a very useful working hypothesis in metallography.

The nature of grain boundaries becomes interesting since it is a fact that replacements observed in minerals are commonly peripheral in character. The replacement appears to commence at the grain boundaries and to work into the grain. If the material effecting the replacement was derived through capillary fissures the peripheral character of the alteration would seem to imply that capillary openings are more common at the grain boundaries. The hypothesis that the material of the boundaries is amorphous accounts for the ingress of replacing material with or without the existence of capillary openings to aid in the movement of replacing material. The relative ease by which diffusion will take place in amorphous, as compared to crystalline, materials accounts for the peripheral nature of replacement at its inception.

If a capillary opening is considered to pass through a crystal

space lattice the existence of an opposing force would be necessary to overcome the atomic forces which hold atoms in their positions in a space lattice. Such openings, larger in size than interatomic spaces, cannot, in the light of our present knowledge of crystal structure, be conceived to pass through a crystal with resultant production of crystal lattice distortion.

Capillary openings then, if such could exist, would therefore be limited to the crystalline grain boundaries. If the material at the grain boundaries is considered to be amorphous, capillary openings cannot exist even here. Amorphous material, while possessing a heterogeneous arrangement of its constituent atoms, is also closely packed as in the case of crystalline material, thus existing spaces in amorphous material would also be on the order of interatomic space. While no forces are in operation in amorphous material tending to produce an orderly arrangement, attractive forces such as do exist between the atoms themselves, must be overcome by some opposing force to yield capillary openings. It should be noted that this does not deny the existence of capillary openings such as exist in surface rocks as, for example, sandstones, and which were made possible by the formation of such rocks.

Such considerations would seem to imply that openings of the order of interatomic spaces must be considered in the movement of material through a nonporous, solid rock mass. The mechanism involved in the transfer of material through interatomic space is that of diffusion.

It is worth-while to consider briefly here the latest ideas of metallographers regarding the nature of diffusion.[2] Diffusion force probably depends largely on: (1) Concentration gradient, and (2) relative attractive forces between like and unlike atoms. The greater the concentration gradient and the more the mutual attraction of the unlike atoms differs from that of the like atoms the greater should be the diffusion force. Diffusion resistance probably depends largely on: (1) Temperature, (2) atom size,

[2] Statements regarding diffusion are taken from, "The Trend in the Science of Metals," Zay Jeffries, *Min. and Met.* Preprint No. 1337–N, pp. 7–8, May, 1924.

and (3) dimensions and type of space lattice. It is easy to understand why the diffusion resistance would be lower the higher the temperature; the space lattice becomes larger and the force required to move the atoms relative to one another is decreased. It is not easy, however, to comprehend why diffusion in the solid state takes place at all. The atoms are very resistant to deformation, as evidenced by the large forces required to deform metals elastically. Steel stressed to 300,000 lbs. per sq. in., elastically, in tension has its space lattice extended only 1 per cent. With such great forces required for so little deformation, it is difficult to understand how two atoms could exchange places. Langmuir has proposed a mechanism that is quite satisfying. Fig. 1 shows schematically a group of atoms of one size enclos-

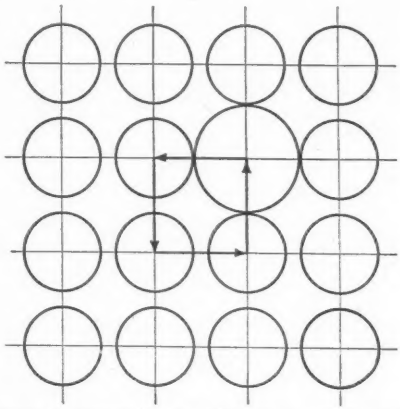

FIG. 1. Schematic conception of diffusion in crystalline lattice.

ing a larger foreign atom. Assuming the matrix atoms to represent tungsten, the larger atom is about the proper size to represent thorium. The concentration gradient is such as to produce a diffusion force from right to left. The movement is effected by a rotation of four adjacent atoms simultaneously. It is obvious that such rotation can take place without greatly disturbing adjacent atoms. The rotation may not always in-

volve four atoms. This mechanism also fits in with the known fact that diffusion is relatively easy in amorphous, as compared to crystalline, materials. In amorphous materials, the rotational movement would take place in any direction and the atoms or molecules probably have rotational movement in addition to that due to temperature.

The geological effects of diffusion have been much discussed but, as Whitman [4] points out, "It has been assigned an important rôle in metamorphism, in banded weathering, and in certain ore-forming processes; but either by silence or direct imputation it has been denied recognition in its true rôle as a prime agent in the formation of all metasomatic deposits." The term metasomatic (or replacement [5]) is common in geological literature but the importance of the process is one aspect of the subject in which very little, if any, agreement exists. The various viewpoints of the relative efficacy of this process in the genesis of ores may be well illustrated by reference to the following recent articles. Schneiderhohn [6] states that, "'replacement' is at this time one of the shibboleths [7] in American mineral deposit literature and although replacement doubtless plays a very important rôle it has not brought about everything." Howe,[8] on the other hand, in the case of the gold ores of Grass Valley,

[4] "Diffusion in Vein-Genesis at Cobalt," Alfred R. Whitman, ECON. GEOL. vol. 15, No. 2, March, 1920, p. 137.

[5] Replacement is analogous to metasomatic. "Volume Changes in Metamorphism," W. Lindgren, *Jour. Geol.*, vol. 26, No. 6, Sept.–Oct. 1918, p. 543.

[6] "Mineralogical Observations on Copper, Lead, Zinc and Vanadium Deposits of the Otavi Mountain Region, German South-West Africa," Hans Schneiderhohn, *Neues Jahrbuch* Supplement, vol. 43, 1920.

[7] This is a rather unusual term and since used, seemingly, in an indictment of the American geologist, it may be advisable to give the definition from Webster; It is an ancient Hebrew word meaning an ear of corn, a stream, or a flood. Its more recent usage developed as a result of a Biblical reference. This was the word by which the Gileadites distinguished the fugitive Ephraimites at the Jordan fords. The Ephraimites not being able to pronounce *sh*, called the word sibboleth. Hence its usage as the criterion, test, or watchword of something, as a party; specifically, a party cry or *pet phrase*.

[8] "The Gold Ores of Grass Valley, California," Ernest Howe, ECON. GEOL., vol. 19, No. 7, Nov., 1924, pp. 595–619.

believes replacement to have been the predominating process in the genesis of the ores. In the discussion accompanying Howe's paper Spurr assigns a minor rôle to replacement in Grass Valley. References of this nature might be prolonged almost indefinitely. It would appear as though consideration of the relative efficacy of replacement processes must first be based upon a proper understanding of the manner by which such processes operate. Doubt even exists in regard to the validity of certain criteria by which replacement structures may be identified. It would be more logical, therefore, to defer judgment until more data are forecoming upon the nature of replacement. Even though a perusal of geologic literature shows that the relative importance of replacement processes in ore genesis is a question in debate, the extensive literature also indicates the widespread recognition of the existence of such processes.

Replacement may take place during the crystallization of an igneous rock, immediately subsequent to this period, or at any time later. The question of terminology presents itself as a result of these various replacement periods. Magmatic covers the first period, that of replacement during the crystallization of rock-making minerals.

The period immediately subsequent to the magmatic period, has been variously designated as deuteric, paulopost, secundine or pneumotectic. Two of these terms, deuteric and paulopost, were first introduced and were presented at about the same time, therefore it should be proper to choose between them. Paulopost appears to be the preferable term. It is a little used word derived from the Latin, *paulo post,* a little after and its meaning, somewhat subsequent, could not possess a more appropriate connotation. Deuteric, derived from the Greek, connotes merely a secondary character.

Any replacement period later than the period of paulopost replacement, may be designated as *multopost,* much later.

It may be well to give an example of the proposed usage of the two latter terms, paulopost and multopost. In the case of an intrusion of granite into an older igneous rock, dikes cutting

the granite and derived from the same magma, may be associated with an alteration of the granite produced by end products of the granite magma. This alteration, and any attendent replacement, would be referred to as paulopost. These end products of the intrusive granite may also produce similar phenomena in the igneous rock which has been intruded. The alteration of the intruded rock took place, in this case, much later than the period of formation of the intruded rock. Applying our term designated especially to distinguish these different time intervals, we refer to this period in the intruded rock's history as multopost. It is to be noted that alterations produced at the same time are designated, in the case of the rock intruded, as being multopost, while in the case of the intrusive rock itself, which furnished the material which produced the alterations, it is designated as paulopost.

Replacements, paulopost or multopost in character, are conceived to be accomplished by the tranfer of material through the mechanism of diffusion. The amorphous character of grain boundaries permits the easy diffusion of replacing materials while transfer by any other means, such as along capillary fissures, is a more or less negligible factor considering the rock mass undergoing replacement as a whole.

There remains to be considered the geological effects of the material replaced. It is also conceived that the material replaced finds its way back to the source of the replacing material by diffusion. If this source should have large dimensions, the contributions of returning material entering by diffusion, would have only a negligible effect upon its composition. It is conceivable, however, in the case of a minor intrusion receiving these contributions that the composition of the mass would be seriously affected. When the great bulk of material lost during replacement of a large rock mass is considered, the change in the composition of a minor intrusion by addition of this material is more readily conceived.

The replacement of a limestone by silica may be cited as a

specific example. Carbon dioxide may be easily eliminated under the temperature conditions which prevail as the result of an igneous intrusion. The heat from the intrusion produces a sufficiently high diffusion force to cause the diffusion of CO_2 to the surface where it will pass into the atmosphere and become lost. The lime, CaO, will not be eliminated since it is known that no appreciable volatilization of CaO takes place below 2000° C. at ordinary pressures such as those under near-surface conditions. Since sufficient heat does not exist to expell the CaO, a diffusive cycle will be initiated by its entrance into the magma. CaO is a very stable molecule and would naturally diffuse as such.

Thus we have a sufficiently large amount of material entering a minor intrusive body to account for the production of a rock type somewhat unusual in character. The CaO entering a basalt would produce a type such as a melilite basalt under these conditions. Bowen [9] states that, "It is probable that some melilite is produced by the addition of lime to ordinary basalts." Shand [10] states that, "for the *under-saturated alkaline rocks* I see no explanation to replace that of Daly—namely, reaction with limestone." The difficulty does not appear to be the reaction with limestone but is the manner by which this reaction is made possible. Diffusion removes the necessity of assuming the direct assimilation of limestone fragments in a magma possessing considerable superheat to produce an alkaline facies, an assumption which Bowen [11] points out is probably erroneous and that any great amount of superheat was non-existent.

The absence of melilite from deep-seated rocks is significant to the view that lime added by diffusion from a limestone undergoing replacement is sufficient in quantity to produce this mineral in a near-surface intrusion of basalt, but is not sufficient to produce this mineral to any significant extent in a deep-seated type.

[9] "The Genesis of Melilite," N. L. Bowen, *Jour. Wash. Acad. Sci.*, vol. 13, No. 1, January, 1923, p. 3.

[10] "The Problem of the Alkaline Rocks," S. J. Shand, *Proc. Geol. Soc. South Africa*, 1922, p. 29.

[11] "The Behavior of Inclusions in Igneous Magmas," N. L. Bowen, *Jour. Geol.*, vol. 30, Supplement to No. 6, Aug.–Sept. 1922, pp. 513–570.

Shand [12] states that, "This continuous addition of lime to the freezing magma by circulating fluids seems to me to offer the best explanation of the abnormally late crystallization of lime minerals, such as melanite, schorlomite, sphene, apatite, wollastonite, pectolite, vesuvianite, cancrinite and calcite in nepheline syenites." If the lime is derived by diffusion incident to the replacement of a limestone, it is to be expected that much of the lime will find its way into the magma, or sub-magma, at a late period even as late as its freezing period.

While diffusion admittedly is a very slow process, the fact that the cooling of an intrusive body takes place very slowly permits sufficient latitude in time for diffusion to operate.

If we consider recrystallization phenomena in the light of the absence or unimportance of capillaries, it will be found necessary to revise the conventional views regarding the mechanism of recrystallization. The metallographer has evolved a satisfactory explanation of recrystallization in which there is no necessity of assuming the existence of capillaries. It is logical to suppose that this mechanism of recrystallization may be used in the interpretation of similar phenomena in geology.

Recrystallization [13] is considered to be merely submicrosopic grain growth. The substitution of a number of unstrained grains of various orientations for a single strained grain, suggests that new crystalline nuclei are formed during the process of recrystallization. It is known, however, that the strained grain has within it an abundance of nuclei in the form of fragments produced by deformation. It is more logical to suppose that recrystallization consists in the growth of some of these fragments to visible size than that entirely new nuclei are formed. A strained grain may be regarded as an aggregate of a large number of crystalline fragments, each equivalent to a very small grain.

An objection to the view that recrystallization is merely sub-

[12] *Op. cit.*, p. 30.

[13] The following statements regarding recrystallization are taken from "The Science of Metals" by Jeffries and Archer.

microscopic grain growth is found in the belief held by some that during plastic deformation the grain fragments retain substantially their original orientation. It is a fact that the new grains which form from a strained grain upon proper heating have orientations which may differ from that of the original grain. If these new grains are held to have grown from the fragments of the old grain, then it must be considered that the fragments which acted as nuclei also possessed different orientations.

In view of the fundamental importance of the question some experiments were made by means of x-ray analysis to determine whether or not new orientations are produced by deformation. The evidence was conclusive that new orientations are produced by the simplest types of deformation such as rolling or pressing. This removes the only valid objection to the view that recrystallization is merely grain growth.

Grain growth obviously results from the tendency of matter to assume the form of greatest physical stability, which is the form of least energy. The crystallization of metals from the liquid state is always accompanied by an evolution of heat, representing the loss in the kinetic energy of the atoms incident to their fixation in the rigid crystal lattice. The atoms at the surface of a liquid or solid body are less subject to the attraction of their neighbors than are the atoms in the interior. They are therefore more free to move and consequently possess more energy of motion. A "free" surface of a body is thus the locus of extra energy, known as "surface energy" or sometimes "surface tension." There is, therefore, a tendency for the small particles, such as drops of a liquid or crystals of a solid, to unite to form larger particles, since in so doing they diminish their surface area and hence their total energy. It follows that the most stable form for any piece of metal would be a single crystalline, grain. To have the smallest possible surface area, this grain should be spherical in shape. This would not, however, necessarily give the minimum surface energy, because of the geometri-

cal properties of the crystal. The most stable form for a crystalline substance is often an idiomorphic form built up of the natural crystal faces. On the other hand it is well known that small particles of certain crystalline constituents in a metallic aggregate tend on long heating to assume a spherical form. The most stable form of a metallic crystal may be stated as being that of least surface energy, which will probably be either idiomorphic or spherical. Obviously, any roughness on the surface of a crystal is a source of increased surface energy, and hence diminished stability. The fact that, even after prolonged annealing above the recrystallization temperature, grains may be found having jagged or irregular outlines would represent a condition of greater thermodynamic stability.

If a crystal is subjected to an external load below its elastic limit, it becomes temporarily deformed or distorted. On release of the load, the crystal returns to its original form. The deformation of the crystal by the external load requires an expenditure of energy which is stored in the crystal itself and manifested by its ability to return to its original shape, doing work as it returns. An elastically deformed crystal thus contains more energy than a similar crystal free from stress and distortion, and is therefore less stable thermodynamically.

It is held that energy is required to impart the power to grow, and that this energy must be stored in some way in the grain. The strained grain is, therefore, regarded as the one endowed with the power of growth. Actually the conditions are the exact reverse. The unit which does the growing is the grain of greatest thermodynamic stability, and hence *least* energy content. The logic of this apparent on considering the conditions on the solidification of a metal from the molten state. The solid, unstrained grains feed upon the molten phase, which has the higher energy content.

This is in line with the studies of Leith [14] who shows that the mineral strained (with greatest energy) dissolves most easily which is in agreement with the statements above that the unstrained grain (least energy) is the one that grows.

[14] "Rock Cleavage," C. K. Leith, U. S. G. S. Bull., 239, 1905, p. 69.

All the factors have now been briefly considered which, accord- to present knowledge, may influence the stability of a crystal—namely size, form, surface and distortion.

Grain growth takes place by a process of boundary migration which involves the gradual transfer of atoms from the lattice of one grain to that of the adjacent grain. Whether or not this transfer takes place through a layer of amorphous grain boundary metal, it requires a certain degree of atomic mobility or temperature for its accomplishment.

The relative importance of the factors affecting the stability of the grains (size, shape, surface and distortion) will now be considered.

General observations on the effect of grain outline or surface on grain growth phenomena are lacking so that this factor cannot be incorporated as basic in a theory of grain growth.

The principal conditions conducive to grain growth are small grain size and grain size contrast. A crystalline grain is to be regarded as an organized structure having a definite power to hold its atoms in their positions in its space lattice, and to attract neighboring atoms into its lattice. This power is due to the cumulative effect of the directional force fields of the atoms composing the grains. The exact nature of these force fields is not known, consequently the manner of their linkage is unknown. It is held by some students of atomic and molecular physics that the attractive force of an atom does not extend to a distance of more than two or three atom diameters, in which case the orienting power of a crystal would be very little affected by its size when such a crystal contained more than about six atoms across its smallest diameter. Jeffries and Archer believe that the influence of the atoms within a crystal upon its orienting power extends to a much greater distance. In any event, it is certain that large crystals or crystalline grains do possess that property which has here been called "orienting power" to a greater extent than do similar crystals of smaller size.

The concentration of a saturated solution in equilibrium with

an excess of solid salt is greater the smaller the particles of the solid. This can mean only that the small particles are less capable of attracting atoms or molecules from solution than are the larger particles.

Chemically speaking, the solution is unsaturated with respect to the smaller crystals but supersaturated with respect to the larger crystals. The former therefore dissolve and the material thus removed precipitates upon the larger crystals. The general principle here illustrated is that in an aggregate of grains of various sizes, the larger grains tend to grow at the expense of the smaller. If a condition is assumed in which all of the grains are of exactly the same size and similar in other respects, there is a balanced condition with no opportunity for grain growth, even though the tendency for growth is present, due to the fact that the thermal stability of the aggregate would be increased by an increase in grain size. The grains all possess equal powers of orientation, however, so that there is no resultant growth force.

Grain growth is controlled by three factors: (1) grain size relative and absolute which determines the growth force or tendency for growth to occur; (2) temperature, which is equivalent to atomic mobility and determines whether the growth force can overcome the rigidity of the metal; and (3) obstruction, which mechanically hinders and sometimes entirely prevents grain growth.

There is an apparent equilibrium grain size for each temperature. As the temperature of the metal is raised, grain growth takes place until the growth force is reduced to a point where it can no longer cause growth under the existing conditions of temperature and obstruction. The metal is in the state of metastable equilibrium as regards grain growth. In this condition the grains are usually fairly equal in size.

As Leith [15] points out, in a given rock the uniform size of the particles of one mineral species produced by recrystallization is not the same as that of another mineral species. The same min-

[15] *Op. cit.*, p. 77.

eral species assume a uniformity in the size of grain. This is a consequence of the variation in the geometrical properties of different mineral species.

One other theory of grain growth, the distortion theory, remains to be considered. According to this theory held by some, grain growth has been considered to be caused by varying distortion of the crystal lattice. It is known that when a metal is cold worked, internal stresses are left which must necessarily involve elastic distortion of the grains or grain fragments. It is also quite certain that the amount of relative distortion varies from grain to grain. The grains which are distorted the least are most stable and are, from the thermodynamic point of view, in a position to grow at the expense of the more severely distorted crystalline material. The distortion theory postulates that when such growth takes place, the atoms added to a grain arrange themselves in a lattice having exactly the same degree of distortion as that of the growing grain. Grain growth then involves a progressive decrease in the elastic energy of the metal due to lattice distortion. At any given temperature a state of metastable equilibrium is reached. On heating to higher temperatures the decreased inertia enables more growth to take place always with a differential distortion as the cause. This theory fits in well with many of the grain growth phenomena but depends upon the assumption that lattice distortion and hence internal stress, exists in metals which have been fully annealed. The effect of heat upon internal stresses has been fully investigated in connection with the season cracking of brass, and it has been found that these stresses are reduced to a vanishing point by heating *below* the temperature of recrystallization. It does not therefore seem likely that at temperatures several hundred degrees higher any appreciable distortion can exist. The surface energy due to small grains is present at all temperatures and can be reduced only by grain growth. On the other hand, cast metals can be obtained in a condition of internal stress nearly equal to the elastic limit and involving practically the maximum possible

lattice distortion in some of the grains. This distortion can be removed on heating without causing any grain growth. Such considerations lead to the conclusion that surface energy is the principle cause of grain growth.

Leith's paper of 20 years ago remains a valuable contribution at the present time which can be recommended to the metallographer for study. With revision omitting the necessity of assigning an important rôle to water existing in capillaries, the paper, as a whole, has lost little value with time. Leith[16] did state that, "there is evidence that changes between solid particles may occur, to a yet unknown extent, without the intervention of water, but the important process is believed to be as above described," involving solution in water.[17]

It is hoped that this paper will show how the science of metallography has opened new avenues of thought with reference to such geological processes as replacement and recrystallization and that much may be accomplished by mutual aid between this science and geology.

[16] *Op. cit.*, p. 69.

[17] Dr. Alfred C. Lane, well-known for his studies of the grain of igneous rocks, directs my attention to the omission of any reference to the importance of the rate of temperature change upon grain size.

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EDITORIAL

SOME POSSIBLE LINES OF RESEARCH ON ORE DEPOSITS.

ANY branch of science in its youthful stages has certain characteristic features. New fields are opened to observation, descriptive data rapidly accumulate and minds are active in seeking explanations. In this early stage, copiousness of description and fertility in hypotheses are dominant.

Imagination is the animating spirit of science as in art. From it spring hypotheses and speculation. Without hypotheses, the gathering of facts becomes aimless drudgery. Even speculation, in spite of its connotation of irresponsibility, may have some stimulant quality. The results of speculation, however, have no finality; they are of value only in so far as they suggest and give direction to the patient observation of facts and the experimental testing of possibilities.

No one, I believe, can review the literature of ore deposits without being convinced that descriptive material and unverified hypotheses vastly preponderate over the demonstration and application of principles. Our science is young and such are its inherent difficulties that it seems likely to retain its appearance of youthfulness for a longer period than we can forsee. Ore deposition takes place at depths beyond our range of observation, under complex conditions widely different from those with which we are familiar, and demands periods of time in comparison with which the life of a man is but a fleeting moment. There is scarcely an ore deposit concerning which we are in full agreement as to its origin. One writer states confidently, "It is very evident that the metals in this deposit have been given off as volatile emanations from a near-by igneous rock." Another is

equally sure that the igneous rock had no essential part in the ore genesis. Still another remarks politely, "You are both in error; the deposit was injected in a molten condition as a veindike." Others are ready to enter the discussion but I will hasten to remark that such diversity of opinion could hardly exist did the science of ore deposits rest more firmly on ascertained truth and demonstrated principles. As a matter of fact, not one of the geologists in this not wholly imaginary instance really knows that his statement is true. In the face of this situation some courage is required to maintain an optimistic attitude as to future progress but courage and patience are not uncommon scientific virtues. The purpose of this editorial is to suggest some of the directions in which these qualities may find application.

Notwithstanding the great volume of modern descriptive writing on ore deposits there is still ample opportunity for work in this field. Not only are ore deposits extraordinarily varied but inasmuch as many are in process of active industrial development, new aspects of these are constantly being exposed and new facts worthy of record are continually being brought to light. There is no limit to the number of observations that might be recorded for a single deposit. Any description must be selective and the most valuable description is that in which accuracy of observation is combined with a broad realization of the chief problems of ore genesis, an open and impartial mind, and something akin to an intuitive perception of what may in future be of value. Such is the material that may be put to use by others in the verification of hypotheses or the recognition of principles.

Over vast areas of the earth's surface the ore occurrences have as yet received scarcely any detailed study from trained geological observers. One conspicuous example, close to our doors, is Mexico, which in the number and variety of its ore deposits stands supreme among the countries of the world. Some excellent papers have appeared by Spurr, Garrey, Lindgren, Bergeat, and others but it is impossible to review the literature of Mexican ore deposits without realizing how few of them have received adequate descriptive treatment from the geological point of view.

It is generally recognized that around a mass of intrusive rock the ore deposits exhibit a concentric zonal arrangement with respect to their mineralogical character and metallic content. The evidence upon which this conclusion rests, however, has only in small part been gathered together in accessible form. W. H. Emmons has devoted several years to this work but his voluminous collected material and his results are as yet unpublished. There is ample opportunity for others to contribute facts regarding such zonal distribution and to determine the laws that govern it.

A similar statement might be made with reference to the influence of country rock on ore deposition. Mr. Spurr in the March–April number of this journal describes a most interesting case, that of the Camp Bird vein, where a change in country rock has had pronounced effect on the character of the vein. He offers an ingenious explanation which should be tested by observations on other deposits.

A specific problem that may be mentioned in this connection is that suggested by the common association of cinnabar deposits with serpentine in the Coast Ranges of California. The serpentine is probably Jurassic whereas the quicksilver deposits are Tertiary or younger. Why are so many of these deposits in or near the serpentine?

The influence of wall-rock on ore deposition is undoubtedly of more than one kind and involves many complex factors. There is opportunity here for a comprehensive study which should rest not only on first-hand observation but could utilize also published descriptions of sufficiently detailed accurate character. Such descriptions, however, are not any too abundant.

There is, as is well known, wide divergence of opinion as to the mode of deposition of epigenetic ore bodies. There are those who, impressed by the chemical activity and mineral contents of hot-spring waters, regard a large group of deposits as having been gradually built up by the accumulation of successive crusts of minerals precipitated from similar waters on the walls of open cavities. There are those who look upon the same ore bodies as

due to the crystallization of a molten " ore magma " injected with such force as to open or form the spaces in which they now lie. Still others consider that the pressure exerted by growing crystals is competent to force apart the walls of small fractures and provide the space for large ore bodies although it would seem that the continued entrance of additional ore solution or ore magma would be opposed or even prevented by this same pressure. Inasmuch as there appears to be no basis for a definite distinction between a hot aqueous solution and a molten magma, there is opportunity for various shades of opinion between those here so briefly outlined. The recent able and suggestive summary by H. C. Boydell on the rôle of colloidal solutions in the formation of mineral deposits indicates that neither the proponents of deposition from mobile aqueous solutions nor the vigorous advocates of viscous intrusion have exhausted the possible explanations for some of the perplexing features of ore deposits. The idea that certain ore deposits may have passed through a gel stage, with the formation of openings due to shrinkage and crystallization of the mass with the consequent opportunity thus provided for the entrance of new material, is at least highly suggestion of a possible explanation of some ore-structures. Finally the process of diffusion through wet or moist rock, as Whitman has shown, can not be ignored in our present imperfect stage of knowledge. The amygdules in volcanic rocks can scarcely be conceived of as due to the circulation of water in the ordinary sense or to viscous intrusion. Yet in some respects they are significantly analogous to ore-bearing veins, particularly to some of the chalcedonic veins of Tertiary age. This thought leads to the inquiry whether the theory of lateral secretion, now somewhat out of fashion may not, after all, perhaps in modified form, be applicable to some ore deposits. The actuality of the process of supergene enrichment and its general mode of operation, especially with respect to copper ores, are well established. Nevertheless, with reference even to deposits so carefully studied as those of Butte, we are still in doubt as to the respective parts played by hypogene and supergene deposition. Evidently defi-

nite criteria for distinguishing hypogene and supergene mineralization have not yet been found. Finally, we are still awaiting a completely satisfactory explanation of the origin of the native copper ores of the Lake Superior region.

The conclusion that may, I think, be fairly drawn from this necessarily brief confession of ignorance is that we are much in need of experimental work in ore deposition of a quality equal to that which has been carried out, chiefly with reference to the origin of igneous rocks, in the Geophysical Laboratory of the Carnegie Institution of Washington, or that on the effects of pressure conducted by Bridgman at Harvard. It should be possible to obtain by experimentation some fundamental data as to the behavior of silica, water, sulphur and metals under conditions of temperature and pressure approximating those under which ore deposition has taken place in nature and in this way to substitute definite knowledge for some of our present conjecture. The weak point in much discussion of ore genesis is lack of information as to the physical chemistry involved.

The interest of geologists naturally turns to problems of ore genesis but there is another problem of great practical importance that has been attacked with fine spirit and ability by Dr. Augustus Locke and his assistants, namely, "How far is it possible to determine from the character of a weathered outcrop the nature of the material beneath the surface?" Of course, in a crude way, prospectors from time immemorial have used the appearance of the surface as a guide to underground exploration but it has remained for Dr. Locke to attempt to interpret the surface conditions in a definite and quantitative way. He has devoted his attention particularly to copper deposits but the investigation may well be extended to the ores of other metals. It is easy to see difficulties in the way of such a study. The conditions of oxidation and erosion of an ore body other than one of very simple character, are enormously complex and in grappling with this problem Dr. Locke has shown remarkable courage and determination. Other geologists might well contribute additional ob-

servations and investigations in this general field which is too large to be covered by any one man.

In conclusion, I would suggest that the prime necessities for progress in the science of ore deposits are greater refinement, accuracy and discrimination in description and the establishment of fundamental chemical and physical data by experimental work. Without any suggestion that the use of the imagination should be discouraged or curtailed, writers on the problems of ore genesis may well be reminded that in our present state of knowledge, a modest realization of ignorance may well temper the enthusiasm with which some ideas are set forth and that suspension of judgment is not necessarily to be branded as timidity or aversion to real progress.

F. L. RANSOME.

DISCUSSION AND INFORMAL COMMUNICATIONS

GENESIS OF IGNEOUS ORE DEPOSITS.

Sir: In his review, in the Sept.–Oct. number of ECONOMIC GEOLOGY, of my paper on the origin of primary ore deposits Mr. Robert B. Sosman raises two points that it may be of interest for me to explain more fully from my point of view.

1. It certainly was an essential premise in the first part of my paper that *primeval siliceous magma* was originally "dry." By primeval magma I mean one that comes into existence for the first time in a cooling system after the formation of the radicles composing it. The temperature at which this formed was higher than that necessary for expelling the last traces of water when a system (of the same composition otherwise) is being raised in temperature in the laboratory. An essential factor is being neglected, however, *i.e.*, pressure. I admit that in the laboratory at atmospheric pressure a silicate will not take up water at the temperature necessary for expelling the last traces of water from it. But the reverse is true at elevated pressures otherwise hydrous silicates could not come into existence at all. Let us assume two silicate mixtures similar in weight and of exactly the same ultimate composition one at 3,000° and the other at 15°. Let the former cool very slowly to 2,000° and heat the other very slowly to 2,000° (the end pressure being the same in both cases) the minerals, molecules or aggregates of combined radicles certainly will not be identical in both. If this be not appreciated we are liable both to misinterpret the results of experimental work and to come to false conclusions regarding the nature of the cooling process in rock magmas.

2. The second point concerns the relations of water and silica.

The evolution of ore minerals is so bound up with magmatic differentiation that it cannot be adequately treated separately.

Mr. Sosman admits that water even above its critical temperature "will take up silica and render it invisible, depositing it later as quartz." This silica-water apparently exists as a liquid under magmatic conditions. I believe it to be combined in granitic magma and set free on crystallization. In its presence (taking specific minerals) biotite and orthoclase remain liquid far below their normal melting point and ultimately develop in crystalline form, which they will not do at as low a temperature from any other known medium. Without water, crystallization of a mixture of silica, orthoclase, and biotite, will not take place. Without free quartz a mixture of water, orthoclase, and biotite will not crystallize. From a mixture of silica and water quartz crystallizes. For the crystallization of orthoclase and mica both silica and water are necessary. We do not know the nature of the reactions that take place but the above facts compel me to regard them as chemical and not merely physical.

Take a simple solution such as common salt and water and heat it under pressure, as soon as 375°, the critical temperature of water, is exceeded the water all passes into the gaseous condition leaving solid NaCl. Silica and water do not act similarly, they maintain the liquid phase far above 375°. I consider this adequate reason for asserting that at elevated temperature and pressure chemical combination takes place between silica and water and that what we have called silica-water is really either molten silicic acid or a solution of silicic acid in water. The behavior of certain silicates when decomposed by hydrochloric acid is such as to lead us to suspect that both ortho- and meta-silicic acids are capable of existing in solution at 15° and 760 mm. Other evidence of the existence of silicic acid at high temperatures and pressures is furnished by experiment. The ultimate result of the heating of a basic igneous rock with water under pressure is a residue of bases, mostly oxide of iron, the silicates being entirely broken up and the silica removed by the water. I cannot conceive of silicates being broken up by water, the silica removed

and free bases left unless under the conditions ruling at the time silica has a stronger chemical affinity for water than it has for the bases from which it is separated. If the water of rock magmas exists largely in combination with silica we can make certain important deductions. Oxy-acids when present with normal salts of the same acids often combine with them forming double or acid salts much more fusible than the normal salts and which are capable of acting as fluxes. A flux is a substance which when heated with certain other substances causes the whole to assume the liquid condition below the normal point of any component. That this action is purely physical may reasonably be doubted; it is more likely to be due to the formation of complex unstable molecules of low melting point which break up on reduction of temperature and pressure. Potash and soda form acid salts much more readily than lime or magnesia and they are specially prone to enter into complex molecules when combined as double salts with alumina.

When primeval magma breaks up into acid and basic fractions it is notable that the essential minerals of the latter are all capable of formation by the simple fusion of their component oxides whereas the essential silicates of the acid fraction cannot be formed by dry fusion but all require the presence not only of water but of free silica. This being the case I am strongly of opinion that a granitic magma consists, not of mica, feldspar, silica and water in mutual solution but of complex acid silicates of low melting point in which the whole of the water is present as hydroxyl; that crystallization is the result of the breaking-up of these complex silicates, mica first being deposited and silicic acid liberated and next, usually, feldspar with the liberation of more silicic acid and lastly quartz which is the result of the dissociation of silicic acid itself; and that it is only on the process reaching the last stage, the formation of quartz, that any water whatever exists as such in the magmatic process.

The ore minerals which are frequently products of the cooling of granite magmas I regard as mostly existing there in complex silicate molecules which break up at temperatures and pressures

lower than do those yielding mica and feldspar. The possibility of the existence of complex silicate-sulphide molecules is demonstrated by lazurite but few of them appear to be stable under ordinary conditions.

Tin and silicon are related elements, their chemical behavior being similar in many ways. The stannic acids are very similar to the silicic acids and there is reason to believe that when an aqueous solution of stannic acid under magmatic conditions is cooled it dissociates, depositing anhydrous stannic oxide in crystalline form—cassiterite. Further, at lower temperatures wood-tin, which is analogous to chalcedony, is formed.

I believed in 1920 that tin existed in magmatic liquids in combination with silica but study of deposits in which tungstates and cassiterite occur in the same veins convinced me that the mode of combination of the two in magmatic liquids is essentially different and that their development in crystalline form is due to different causes. When wolfram and cassiterite occur in contact with one another the former is almost always developed first. This is very marked in Cornwall yet in the same lodes cassiterite persists through a greater vertical range and to greater depth than wolfram. Whether associated with cassiterite or not wolfram crystals invariably contain an appreciable amount of tin but not necessarily as cassiterite. Even when developed in the vicinity of wolfram cassiterite rarely if ever contains an appreciable amount of tungsten.

Tungsten probably travels in magmatic liquids as silico-tungstate and tin as stannic acid. The causes of development of tungsten ores and of cassiterite from these liquids are not known but undoubtedly they are dissimilar and the former is the more obscure.

There is much evidence indicating that the formation of crystalline cassiterite and quartz, also of crypto-crystalline wood-tin and chalcedony is due to the same chemical process proceeding under varying physical conditions, *i.e.*, the dissociation of acid molecules in a cooling liquid system into a solid anhydride and water. Such a process is quite normal.

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The intervention of a gaseous phase demanded by the pneumatolytic theory of the origin of cassiterite is quite abnormal for the change from the liquid to the gaseous state of both the tin fluoride and water involves the absorption of much heat, and where it is to come from in a cooling system in process of crystallizing I gladly leave to supporters of pneumatolysis to explain.

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DEVELOPMENT OF ORE DEPOSIT THEORIES IN EUROPE.

Sir: In his instructive essay "The Origin of Metallic Concentrations by Magmation,"[1] J. E. Spurr gives a review of the theories concerning the formation of ore deposits. In this connection he discusses particularly the contrast between the lateral secretion theory and the magmatic water theory, and refers to to the former as the German, and to the latter as the French school.

Anyone acquainted with the development of theories concerning ore deposits in Europe knows, that it is altogether unjustifiable to refer to the theory of lateral secretion as any one national school and to the magmatic water theory as any other national school. It is true, to be sure, that the great French scientist Elie de Beaumont formulated the volcanic emissions theory in the modern way. It is also true that since then no other theory has been able to gain a foothold in France, presumably because scientific activities are centralized in France as in no other country. The authority of a scientist like Elie de Beaumont necessarily made itself felt for a particularly long time. But similar theories had already been formulated by others long before Elie de Beaumont, as, for example, even in the seventeenth and eighteenth centuries by the German scientists Becher[2] and Lehmann.[3] To be sure at that time all geological

[1] ECON. GEOL., vol. XVIII., 1923, p. 617.

[2] "Actorum laboratorii chymici Monacensis seu Physicae subterraneae," libri II., Frankfurt, 1669.

theories were still incomplete and fantastic. After the victory of vulcanism over neptunism, the modern theories of the formation of ore deposits by ascension gained recognition in Germany as well as in France. Thus some time before Elie de Beaumont published his "Note sur les émanations volcaniques et métallifères,"[4] C. G. A. von Weissenbach wrote: "Most of the modern German geologists regard the metallic veins as deposited by sublimation or as the residue of mineral springs."[5]

The ideas fundamental in the lateral secretion theory were also stated in more or less fantastic form by various scientists[6] as early as the eighteenth century. This theory found its most ardent champions in the second half of the nineteenth century in the German scientists Sandberger and Bischof. Through the influence of Sandberger this doctrine spread to North America, where it maintained itself during several decades as the only recognized one. Nevertheless it is wrong simply to call the lateral secretion theory by any national name, for not only have some scientists in other countries, contemporaneously with and also before Sandberger, supported similar views, as for instance Dieulafait[7] in France and Wallace[8] in England, but one must also bear in mind that Sandberger's theory never obtained such general recognition in Germany as it did in North America before 1890. In Germany there was always a large group of

[3] "Von den Metallmüttern und der Erzeugung der Metalle," Berlin, 1753.

[4] *Bull. Soc. Géol. de France,* II. ser., vol. 4, 1847, p. 1249–1332.

[5] C. G. A. v. Weissenbach, "Über Gangformationen. Ein Fragment." Published in: B. Cotta, "Gangstudien oder Beiträge zur Kenntnis der Erzgänge," Freiberg, 1850. Weissenbach had written the cited paper shortly before his death in 1846.

[6] Delius, "Vom Ursprung der Gebirge und der darin befindlichen Erzadern," Wien, 1770.

Gerhard, "Versuch einer Geschichte des Mineralreichs," Berlin, 1781.

Lasius, "Beobachtungen über die Harzgebirge," Hannover, 1789.

[7] L. Dieulafait, "Existence de baryte et de la strontiane dans toutes les roches primordiaires, etc. Filons métallifères à gangues de baryte," *Comptes-rendues Acad. Sci. Paris,* vol. 87, 1878, p. 934. Further notes by Dieulafait concerning lateral secretion are published in the same journal, vol. 89, 1879, p. 453, vol. 96, 1883, p. 70 and vol. 98, 1884, p. 568 and p. 634.

[8] W. Wallace, "The Laws which Regulate the Disposition of Lead Ore in Veins Illustrated by the Mining Districts of Alston Moor, London, 1861.

eminent scientists who opposed the lateral secretion theory. Even the ideas of v. Groddeck [9] are more akin to the ideas of Posepny than to those of Sandberger. In still closer agreement with our modern views are the theories which Cotta [10] formulated as early as the middle of the last century. Furthermore, immediately after Sandberger had formulated his theories, he was very energetically and successfully opposed by Stelzner.[11] Likewise Beck,[12] the well known teacher of economic geology in Freiberg, although he has recognized the validity of the lateral secretion theory in a limited—and well justified—domain, adopts for the rest a point of view similar to that of Stelzner. Thus the magmatic water theory seems always to have more supporters in Germany in the last half century than Sandberger's lateral secretion theory.

A survey of the development of ore deposit theory during the last century makes it clear that although our views have gained in precision and rigor, the increase in the number of fundamentally new ideas of theoretical importance is very small. It can be shown that nearly all theories of ore deposition were formulated, fundamentally at least, as early as the eighteenth century, though in more or less fantastic form.

Also Spurr's theory of the formation of metallic veins by

[9] A. von Groddeck, "Die Lehre von den Lagerstätten der Erze," Leipzig, 1879. P. 331, he quotes the different theories on vein-filling as: "Congenerationstheorie, Lateralsekretionstheorie, Descensionstheorie, Ascensionstheorie," and then he says: "Wir sehen, dass eine Erklärung nicht für alle Gänge passt, und dass die verschiedenen Forscher, welche die angeführten Theorien aufstellten, nur darin fehlten, dass sie aus einzelnen Fällen richtig abgeleitete Anschauungen unlogisch verallgemeinerten."

[10] B. v. Cotta, "Die Lehre von den Erzlagerstätten," Freiberg, 1859. P. 187, he says: "So zeigt sich also nicht nur die Möglichkeit, sondern auch die Wahrscheinlichkeit der Erzgangbildung als eine sehr mannigfaltige, stets aber scheint sie in einer gewissen Verbindung mit nachbarlichen, oft kurz vorhergehenden Eruptionen von Eruptivgesteinen gestanden zu haben."

[11] A. W. Stelzner, "Die Lateralsekretionstheorie und ihre Bedeutung für das Pribramer Ganggebiet." Berg- u. Huttenm., *Johrbuch d. k. u. k. Berg-akad.*, vol. 37, 1889. A. W. Stelzner, "Beiträge zur Entstehung der Freiberger Bleierz- und der erzgebirgischen Zinnerzgänge," *Zeitschrift f. prakt. Geol.*, 1896, pp. 377–412.

[12] R. Beck, "Lehre von den Erzlagerstätten," Berlin, 1901.

magmation is by no means new. It was widespread in Europe in the first half of the nineteenth century after the victory of the vulcanistic views over Wernerian neptunism. Petzold [13] thought all ore veins to be magmatic injections; even Elie de Beaumont regarded some iron ores as intrusives,[14] and some of his sentences prove evidently, that many geologists of his time had views very similar to the views of Spurr;[15] but Elie de Beaumont himself did not approve these views.[16]

The most ardent champion of the magmation-theory in the last century was the Frenchman Fournet.[17] In the twentieth century Weinschenk [18] declared the pyrrhotite-lodes of Bodenmais in the Bayrische Wald as magmatic injections; Vogt and Brögger had similar views regarding some Scandinavian sulphide-ores.[19]

[13] A. Petzold, "Geologie," Leipzig, 1845, p. 481–501: Über das Vorkommen der Metalle überhaupt und über das Alter und die Entstehungsweise der metallführenden Gänge insbesondere.

[14] E. de Beaumont, "Note sur les émanations volcaniques et métallifères," *Bull. Soc. Géol. de France*, II. ser, vol. 4, 1847. P. 1262, he says: "Il existe même dans différentes contrées des masses de fer oxidulé et de fer oligiste qui peuvent être considérées elles-même comme des roches éruptives."

[15] P. 1285 of the same work he says: "Beaucoup de géologues sont portés à admettre que tous les filons ont été remplis par l'injection de matières en fusion."

[16] P. 1284: "Tous ces faits qui s'enchainent et qui s'expliquent naturellement lorsqu'on admet que les substances contenues dans les filons sont *volcaniques à la manière du soufre* (= products of sublimation), deviendraient autant d'énigmes inexplicables, si on soutenait qu'elles sont *volcaniques à la manière des laves*."

[17] M. J. Fournet, "Sur l'état de surfusion du quartz dans les roches éruptives et dans les filons métallifères," *Compt.-rend. Acad. Sci.*, vol. 18, Paris, 1844, p. 1050.

M. J. Fournet, "Aperçus rélatifs a la théorie des gîtes métallifères," *Compt.-rend.*, vol. 42, 1856, pp. 1097–1105. P. 1103 of this paper he says: "Des masses a l'état de fusion pâteuse, telle qu'ont du l'être assez ordinairemant celles des filons, ont été capables de maintenir en suspension les fragments des parois qu'elles ont entrainés avec elles au moment de l'injection."

M. J. Fournet, "Aperçus rélatifs a la théorie des filons," *Compt.-rend.*, vol. 43, 1856, pp. 345–352 and pp. 894–900.

[18] Weinschenk, "Die Kieslagerstätten im Silberberg bei Bodenmais," *Abhandl. d. Kgl. Bayr. Akad. d. Wissensch.*, II. Klasse, vol. XXI., 2 Abt., 1901.

[19] Vogt, "Über die Bildung von Erzlagerstätten durch magnatische Differentiation," *Fortschritte der Mineralogie, Kristallographie und Petrographie*, vol. 2, 1912, p. 24.

The theory which Spurr has called the "Zonal theory" and which has been recently much discussed, was, fundamentally at least, already well known to Cotta seventy years ago.[20]

New perhaps is the idea of ore formation by magmatic differentiation which was first introduced into science in definite form by Vogt at the end of the last century. Nevertheless v. Groddeck[21] regards the magnetite deposits of the Taberg type as magmatic segregations; the same scientist believes a similar manner of formation to be possible also for sulphide-ores.[22] Thus the fundamental idea of ore formation by magmatic differentiation has previously been expressed.

Little attention was given also in the earlier decades to the secondary enrichment of sulphide ores. The zones of enrichment had been known for a long time, to be sure; but the true explanation of their formation was found only at the end of the last century.

Thus, although there are but few new ideas to be mentioned, nevertheless the development of theories on ore deposition in the last hundred years has brought with it a great advance, that is, the knowledge that the manifoldness of the ore deposits can not be explained by a single theory. Every theory is correct in the last analysis, *i.e.*, when limited to particular cases, and every theory is incorrect when regarded as of universal validity. The universally valid theory has done great harm since the beginning, not only to the development of theories on ore deposition, but also to geology as a whole. Historical investigations are, in this respect, very instructive. They show us that we can only then achieve our end if we cease to proceed onesidedly and dogmatically, and if we without prejudice take into account all the theoretical possibilities.

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[20] B. v. Cotta, "Die Lehre von den Erzlagerstätten," 2. ed., Freiberg, 1859, Pt. I., pp. 129–131.

[21] A. v. Groddeck, "Die Lehre von den Erzlagerstätten," Leipzig, 1879, p. 142 and p. 278.

[22] *Loc. cit.*, p. 278.

SUDBURY ORE-DEPOSITS.

Sir: The workings in some of the Sudbury mines have now reached a depth of over 3,000 feet; and in the lower levels new facts have been disclosed that to my mind are destructive of the view which maintains that the nickel-bearing sulphides separated from the norite intrusive by a process of magmatic differentiation in situ.

My own observations were made in 1922, in continuation of a general survey of the nickel and cobalt deposits of New Caledonia and Isle of Pines during the war period.

For much valuable information as to the field relationships of the rocks, character of the ore and such like I am indebted to the writings of Barlow,[1] Coleman,[2] Miller and Knight,[3] Howe,[4] Tolman and Rogers [5] and Bateman.[6] More recently I have read with profit the useful paper by Wandke and Hoffman.[7]

General Geology.—The commercially valuable ore-bodies are crush-conglomerates and crush-breccias cemented with sulphides. They are usually sheet-like lenses of variable width lying along the contact between the granite and norite-micropegmatite, or between granite and greenstone; or they occur wholly in norite or in granite, or in greenstone.

The norite has repeatedly been described as a hypersthene-bearing quartz-biotite-diorite that towards the middle grades into a granitic rock with a micropegmatitic structure, and in its more basic phases, passes into true norite and gabbro. Its sill-like mode of occurrence seems to arise from the magma having forced a passage between the outer ring of Laurentian gneisses, schists,

[1] Geol. Sur. Can., 1907.

[2] "The Nickel Industry," Can. Dept. of Mines, 1913.

[3] Ont. Bur. Mines, vol. 22, part II.; Knight, *Min. and Eng. Jour.*, Sept., 1916; also Miller and Knight, "Nickel Deposits of the World," Toronto, 1917.

[4] *Jour. Econ. Geol.*, vol. 9, 1914.

[5] "A Study of Magmatic Sulphide Ores," Leland Stanford Junior University Publications, 1916.

[6] Bateman, Alan M., ECON. GEOL., vol. 12, pp. 391–427.

[7] *Jour. Econ. Geol.*, vol. 19, March, 1924.

and quartzites and the younger Animikie rocks. Profound faulting and igneous intrusion often follow the contact of two unconformable formations that play an important part in the structural features of a country. Such formations are from the nature of things poorly bonded, and when crustal stresses exert themselves, their contact offers a favourable line of least resistance for rock movement, or the uprising of pent-up magmas.

I am inclined to the belief that the norite and granite originated from a batholitic magma underlying all the pre-Cambrian formations in this area.

The norite and granite at the Creighton mine show no evidence of metamorphism, and except at the contact are remarkably fresh. They penetrate rocks of pre-Cambrian age but are not now in contact with any younger formation.

Character of the Ore.—The ore consists essentially of angular, semi-angular and rounded fragments and blocks set in a sulphide matrix. Generally the fragments range in size from small grains up to pieces a foot in diameter, but blocks ranging from 5 to 15 feet or more in diameter are common.

Microscopic examination has shown that many fragments of rock have been in part replaced by sulphides.[8] Replacement has also taken place in the granite, norite, and greenstone. In the Creighton mine the norite is in places mineralized for a distance of 2,000 feet from the hanging wall; and along the contact where the rock has been slightly sheared and brecciated, it has been strongly attacked by the mineralizing agents, producing what is called *spotted* norite.

Creighton Mine.—The main ore-body in this mine is an uneven sheet-like truncated mass with a maximum length of 1,000 feet and a width ranging from 50 to 180 feet. It extends from the surface down to and below the 20th level. The average dip is about 45°. In the upper levels the ore-body occurs along the contact between the granite and the norite. From the surface

[8] The sulphides are mainly pyrrhotite, chalcopyrite and pentlandite. Pyrite, sperrylite, arseno-pyrite, galena and molybdenite are rarer constituents. Magnetite is usually present. Besides nickel and copper, platinum, silver, palladium and osmium are also recovered in subordinate amount.

down to the 20th level the granite is the footwall rock; but at a point a little below the 12th level there is a sudden change in the hanging-wall rock. Here the norite recedes from the ore-body, and the apex of a greenstone dike appears. Thence downwards to the lowest level the greenstone is the hanging-wall rock, completely separating the ore-body and the norite. Similar intervention of greenstone is not exceptional in the Sudbury area.

The change in the hanging-wall contact rock was unknown to the earlier writers whose reflections on the genesis of the ore were of necessity based on the facts disclosed in the upper levels. None of those who supported the hypothesis of magmatic differentiation speculated on the possible divergence of the norite and the ore-body at the lower levels. On the contrary the essence of their postulate was the constant and intimate contact of the two—the one the parent, the other the offspring.

In the cross-cut at the 20th level, after passing through 200 feet or more of greenstone, there was cut what is locally called the hanging-wall ore-body, which is altogether in the granite. Beyond this was found another smaller ore-mass with the granite on its footwall and the norite on its hanging-wall.

The main ore-body sends off spurs of ore into the granite, and generally the body of the granite near the contact is mineralized with sulphides.

Where the norite forms the hanging wall of the main ore-body (as it does above the 12th level) and is in direct contact with the ore, it is " spotted " with sulphides. Besides this, a wide zone of the norite itself lying parallel with the main contact is impregnated with sulphides.

The greenstone is in part replaced and mineralized by sulphides but not to the same extent as the greenstone at the second level of the Crean Hill mine.

Age Relationship of Norite and Granite.—The footwall granite of the Creighton mine extends in a continuous belt to Crean Hill No. 2, and at Copper Cliff it sends scores of apophyses into the norite. For that reason I am of the opinion that the granite is younger than the norite. It is possibly a differentiate of the

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norite magma, and if that be so the age difference may not be great.

At the Murray mine to the north of Sudbury a boss of granite sends dikes into the norite, and is admitted by Coleman [9] to be the younger. Though the relationship of this granite to the Creighton granite is unknown there is no reason to believe that these two did not come from the same parent magma.

The Greenstones.—There are two types of greenstone in the Sudbury area, an older type associated with the quartzites, greywackes, argillites and conglomerates of the Timiskaming Series, and having a pillow and amygaloidal structure, and a younger type associated with the norite-micropegmatite and clearly intrusive. In many places the older greenstone is so highly altered as to approach an amphibolite.

The younger greenstone forms the footwall of the ore-body in many of the mines, from the surface downward, and in the Creighton mine from near the 12th level downwards.

Referring to the workings at the 20th level in the Creighton mine, Wandke and Hoffman affirm, without adducing convincing evidence, that the oldest rock is the greenstone.[10] This view is, I think, untenable. The greenstone has been proved by the mine workings and borings to exist for a vertical depth of over 1,200 feet. The question arises how did this relatively slender sheet find support till the intrusion of the norite and granite took place? If antecedent to the norite and granite, it could not maintain itself without supporting walls of which there is no trace whatever.

The fact that the greenstone penetrates the granite at the 20th level and rises upward between the granite and norite is the strongest evidence that these intrusives were antecedent to the greenstone and furnished the necessary supporting walls. Apart from the trap dikes, the greenstone is clearly the youngest rock in the workings and to this circumstance I ascribe the remarkable development of ore above the 20th level.

[9] Ont. Bur. Mines, vol. 14, Part III., p. 83.

[10] ECONOMIC GEOLOGY, vol. 19, March, 1924, p. 183.

Genesis of Ore-Deposits.—The next major event in the geological history of the Sudbury area was the intrusion of the greenstone dikes between the norite and granite as seen in the Creighton and other mines. This intrusion was accompanied by the formation of fissures along the contact, followed by profound faulting, and consequent shattering and shearing of the opposing rock surfaces.

The last event was the intrusion of the so-called trap dikes which cut alike through the norite, granite, greenstone and the ore-bodies.

To my mind the intrusion of the greenstone magma started the series of pneumatolytic and hydrothermal processes which led to the mineralization of the norite and granite wall-rock, and the deposition of the sulphides cementing the crush-conglomerates and crush-breccias.

Apart altogether from the order of the events that make up the geological history of the Sudbury area, it must be conceded that the impregnation and partial replacement of the wall-rocks, and of rock fragments enclosed in the ore-body itself tend to show that the sulphides are of secondary origin.

In shape, mode of occurrence and structure the Sudbury ore-bodies are, I think, typical contact-replacement bodies.

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REVIEWS

Outlines of the Occurrence and Geology of Petroleum, an Introductory Handbook by I. A. STIGAND, with an appendix on Geophysical Methods as Applied to Oil-Finding, by M. MÜHLBERG. Pp. x, 246, Charles Griffin and Company, Ltd., London, 1925.

This book is of value to the oil geologist chiefly for the elementary but very excellent appendix of some 24 pages on geophysical methods in oil geology, contributed by Dr. Max Mühlberg of Aarau, Switzerland. The main text of the book, except for a certain freshness of method best illustrated by a chapter on "direct indications of petroleum," is too theoretical, somewhat superficial, and likely to prove disappointing to the geologist.

The purchase of a new book in his own subject by the oil geologist is an adventure similar in many ways to the purchase of a lottery ticket—he hopes for the best but expects the worst—and as is the case with the lottery ticket, it is expectation rather than hope which is generally realized. All oil men are optimists. The highly speculative nature of their business requires them to be so. This is perhaps where the geologist comes by that streak of hopefulness—willingness to take a chance—which provides a market for the continual stream of oil geologies which come from the press. The prospectus or preface of each new work offers it not only to the geologist but to the "practical man" as well. I cannot conceive that there is any very continuing market among practical men. Any practical man, as distinguished from the geologist, who had got as far as page 106 of the book under review would be effectually stopped by coming upon the sentence "Non-recognition of the hade of the apex-locus, or the presence of a steeply inclined flank, in axially inclined anticlines, has frequently brought about abortive operations and the acquisition of useless land, more especially in cases where the dip of one side approaches verticality, etc., etc." If this did not eliminate him from the market for future books of the sort, he would no longer be a practical man.

It is the oil geologist, I repeat, who provides the market which makes possible the publication of books on the geology of petroleum and he is a highly specialized expert or, if a student, hopes to become one and has a right to expect a more critical and technical treatment of his subject than

it gets. Attempts to popularize are well enough but they destroy the value of a work for the specialist, usually without making the book serviceable to the non-specialist or so-called practical man.

One is also entitled to ask regarding the experience of the author of a technical work—his preparation for his task. Mr. Stigand, who is hardly known to American oil geologists, states that the materials and views expressed are founded in part "on personal observations and studies made in various regions during two decades" and refers to work in Borneo and Trinidad. His acquaintanceship with the literature of oil geology and oil occurrences, if one may judge from the references in his text, is not adequate to the task attempted. Half of his references are to works published in 1910 or earlier and out of a hundred references, there are hardly more than a half dozen for the very considerable and extremely important literature of the last five years. So important a source as the bulletin of the American Association of Petroleum Geologists, now in its ninth year, he seems to have missed entirely.

The introductory chapter opens with an attempt to define bitumen with the unnecessary detail of a Redwood and jumps to a consideration of available sources of supply and increasing demand. Mr. Stigand is not an alarmist and reaches the very sane conclusion that it is "apparent that the existing oil fields, and indeed, all the regions that have been explored for petroleum, represent but a small proportion of the territories that may be capable of producing oil," wisely noting also that "the science of oil-finding is still comparatively in its infancy."

The second chapter, in the orthodox fashion, concerns itself with the origin of bitumen. This chapter is a better considered treatment of the subject than the usual scissored account but gives entirely too little consideration to recent light thrown on the matter by work with oil shales. The author has a very superficial understanding, if indeed he has an understanding, of David White's contribution of the carbon ration theory —one of the real advances in oil geology which we seem to have made within the past decade.

Anyone interested enough to read about such a controversial subject as the origin of the petroleums, requires two things; a clear statement of the development of our thought or how we have arrived at our present state of mind and a considered statement of the present beliefs.

The third chapter treats of the stratigraphical distribution of petroleum, and stratigraphical considerations, in a manner somewhat more extended than would seem to be necessary for a work of the modest proportions of the one under review. It could have been improved by omitting much of the accent on age and including the consideration of oil reservoir rocks and general features of petroliferous strata which makes up the sixth chapter.

The fourth chapter which deals with the accumulation and concentration of petroleum in relation to structural conditions and the consequent classification of deposits presents a rather novel scheme of classification based on deposits occurring in (I.) horizontal strata (II.) inclined strata, (III.) vertical strata, (IV.) accumulations due to curvature of strata and, (V.) petroleum in highly folded and disturbed strata.

Petroleum deposits are susceptible to an infinite variety of classifications according to characteristic features to be stressed. All deposits might be classified as shallow, medium, and deep; a most servicable classification if cost of mining were the feature of major importance. Mr. Stigand's consideration is that of geologic structure. Several structural classifications have already been put forward and, although much remains to be done before a suitable scheme is developed, it does not seem probable that the Stigand classification is an important contribution.

The author's consideration of the influence of structure is highly theoretical and would be much more valuable if backed by specific examples with occasional maps and sections from actual pools. One can hardly conceive for example, of a modern and adequate consideration of faulted structures, without specific mention of fields of the Mexia-Powell type. It also lacks a critical consideration of the relative value of the various types of structural control. After all, structure only helps form a trap—a tank; consider the lack of limitation if one describes the number of forms in which a tank could be built rather than the forms in which it is usually found. The maps and sections for this chapter, as well as throughout the book, are entirely diagrammatic and the illustrations are of geology from areas which are but little known and, for the most part, of little importance as oil fields.

The fifth and sixth chapters have to do respectively with problems and factors in the movement and accumulation of petroleum and with reservoir rocks and the general features of petroliferous strata.

The seventh and last chapter on direct indications of petroleum is an inadequate treatment of a subject which has been too much neglected. As the author states, "It is, however, by the presence and discovery of direct indications that attention is usually first attracted to petroliferous areas or formations, and that, in conjunction with geological conditions, accumulations of oil and gas are revealed." One might even say more. The fortunes of one of the leading companies of Mexico and of the world, for example, are founded on a group of properties got together strictly and solely on the basis of direct indications—oil seepages.

The author misses paraffin dirt altogether and his hopeful chapter trails off chiefly into a description of the physical characteristics of various asphalts rather than a consideration of their significance.

One cannot agree with all of Mr. Stigand's conclusions as to the value

of direct indications, for example the conclusion on page 154 that "petroliferous areas where abundant and copious exudation and 'surface-shows' occur are more frequently unfavorable for commercial results." One could refer him particularly to Mexico and Venezuela as presenting evidence contrary to his conclusion.

The appendix on geophysical methods as applied to oil-finding by Dr. Max Mühlberg is a concise description of the various physical methods—gravitational, electrical, magnetic, seismic and sonic, geothermal, etc.—which are being used as aids to the geologist. The descriptions are clear and non-technical and there is a welcome relief from the pages of mathematics which usually confront the reader of literature on this increasingly important subject. The appendix also includes a brief bibliography on the subject.

E. DEGOLYER.

NEW YORK.

A Chart Showing the Chemical Relationships in the Mineral Kingdom. By PALMER COSSLETT PUTNAM, M. S. John Wiley & Sons, Inc. 31 pages, 7 by 10. Flexible binding. Folding chart, 18½ by 37.

This chart is primarily designed to aid in the chemical, micro-chemical, or blow-pipe determination of minerals. It is constructed on the co-ordinate system. The vertical margins show each element (and NH_4 radical) which occurs in nature as the dominant electro-positive constituent of a mineral, and each element occurring uncombined but in mineral form. The horizontal margins contain all the elements (and the NH_4 radical) occurring in nature in the electro-positive state but as minor constituents of minerals, also all the electro-negative elements, the common electro-negative radicals, the water molecule, the native elements, and three unknown elements; the latter being listed by their atomic numbers. The symbol Si_xO_y is the heading under which all the silicates are grouped.

By this arrangement all the dominant positive elements are plotted against all the positive elements, and, also, against the negative elements, and the common radicals.

The chart includes approximately 1,600 minerals which are listed numerically and alphabetically in the accompanying text. The method of manipulating the chart is relatively simple. For example: if one finds a positive test for some element or radical in a given unknown he may refer to the chart and discern all the known mineral combinations into which the detected element or radical may enter. This is accomplished by having very small index numbers (in fact, too small to be read with ease) listed in the squares, or "boxes," formed by the intersection of the

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vertical and horizontal coördinates which in turn refer to the numerical index giving the name of the mineral. The chart furnishes no information beyond the name of the mineral and the elements or radicals composing it.

The large number of minerals listed and the comparatively small number of statistical errors in the chart renders it useful as a condensed survey of known chemical combinations in the mineral kingdom, and is somewhat suggestive as to other possible combinations. Similar schemes have been followed by others, but in less detail, and generally for a smaller number of minerals.

In order to avoid the inconvenience due to the bulkiness of a chart of this sort it is usually necessary to have it framed and hung near the laboratory desk. If the present chart were treated in this manner the attractive flexible binding, most of the printed matter of the text, and the linen reënforcement of the chart would become unnecessary. Their omission would not decrease the usefulness of the chart but would greatly decrease its cost.

R. S. POOR.

The Natural History of Crystals. By A. E. H. TUTTON. Pages xii + 287. Kegan Paul, Trench, Trubner & Co., Ltd., London, and E. P. Dutton & Co., New York, 1924.

This is a most readable semi-popular account of Crystallography. In addition to an excellent historical summary, with especial emphasis on the work of Haüy, Mitscherlich, Pasteur, and the recent workers in X-ray methods, the book furnishes a very good general statement of the essentials of the science. Therefore, not only will the general reader, without previous crystallographic training, find an admirably clear and not too technical presentation, but the student of crystallography, optical mineralogy, petrography, and general chemistry, etc., will find both an excellent review of the general aspects of the science, and, in many places, ideas and facts which will be new and instructive. Enantiomorphism, crystal-structure as shown by X-rays, and "liquid-crystals" are discussed in some detail. One might wish that more than two pages had been given to the methods of Fedorow, whose work on "correct setting" and "crystallo-chemical analysis" promises to be of fundamental importance.

The book is well illustrated, containing 32 full page plates, and some 130 cuts.

CHARLES MILTON.

Weltmontanstatistik, I. Die Versorgung der Weltwirtschaft mit Bergwerkserzeugnissen. I. 1860–1922. Kohlen, Erdöl und Salze. Prepared by M. Meisner, F. Enke, Stuttgart, 1925.

This is a statistical study of world production and use of coal, petroleum, salt, potash and saltpeter, published under the direction of the Prussian Geological Survey. It differs from the "Mineral Resources of the U. S." in that it is more comprehensive—dealing as it does to a much greater extent with world statistics; including those of exportations and importations, consumption and uses, the relation between consumption and population, and kindred subjects. The statistics of the less well known producing countries are discussed as fully as those that are better known, and in this respect the volume serves as a convenient supplement to the "Mineral Resources." It is to be followed by a report on the production of the metals. Unfortunately the latest statistics for some of the countries are 7 or 8 years old. The book is embellished with many graphs.

W. S. BAYLEY.

Useful Aspects of Geology. By S. J. SHAND. 8vo x + 197 pages, 23 text figs. London, Thomas Murby & Co., 1925. Price $2.00.

"This little book was written for prospectors, land owners and engineers who have never picked up any systematic knowledge of geology and who are interested in one or the other of the many undertakings that depend for their success on the applications of geology." It is well and clearly written. It deals with such fundamental principles of geology as are necessary to an understanding of geological processes, and describes geological structures and products in such a way that they may be recognized without any great amount of technical knowledge. Although the discussions are simply worded they are thorough enough to be of value to practical men. The book contains short chapters on geological age and structure, igneous, sedimentary and metamorphic rocks and ores, rocks as building materials, water finding, oil geology and engineering problems.

W. S. BAYLEY.

SCIENTIFIC NOTES AND NEWS

A. W. Stickney, of Galesburg, Ill., has returned from the Philippines, where he made a geological examination of the Benguet property.

H. H. Knox has returned to London from Burma, where he spent last winter.

H. C. Richards, professor of geology in the University of Queensland, has returned to Brisbane after a visit to the oil fields of California.

Ralph W. Cheney of the University of California is one of the members of the expedition under Roy Chapman Andrews to the Gobi desert.

Arthur Wade, geologist, has returned to Melbourne after three months spent in investigating oil possibilities in Queensland on behalf of the Commonwealth Government.

James W. Neill, mining engineer, of Pasadena, Calif., who has been developing an iron deposit in Japan, has returned to this country.

H. C. George, formerly of the Bureau of Mines, Ardmore, Okla., is now at the head of a new school of Petroleum Engineering at the University of Oklahoma.

Ray C. Walters, geologist for the Romano Americano, has been making special studies of salt deposits in Roumania since April, 1924; his present address is 126 Calea Victoriei, Bucharest.

R. E. Rettger, formerly of the Department of Geology at Cornell University, is now in charge of subsurface work for the Sun Oil Company at Dallas, Texas.

Douglas R. Semmes, who now has headquarters at Room 951, 25 Broadway, New York City, will during the summer spend most of his time in New Mexico in petroleum reconnaisance.

W. A. Parks, of the University of Toronto, is president of the geological section of the annual meeting of the British Association for the Advancement of Science, which will be held from August 26th to September 2d at Southampton, England.

Charles A. Mitke is investigating claims for Eastern investors by means of a scouting organization which is at present working in Arizona, and may later extend its work to other states.

A. A. Hassan has gone to Snyder, Texas, to superintend the boring of several deep oil wells on the "Marathon Uplift."

S. H. Cathcart has resigned from the U. S. Geological Survey to take up work in Argentina.

E. DeGolyer, vice-president and general manager of the Amerada Petroleum Corporation, 65 Broadway, New York, and president of the

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American Association of Petroleum Geologists, delivered the commencement address at the Colorado School of Mines on May 15, 1925, the subject of his address being "The New Frontiers." It was considered one of the finest commencement addresses ever delivered at the school.

In recognition of Mr. DeGolyer's standing as scientist, scholar, and executive, the School of Mines conferred on him the honorary degree of Doctor of Science.

F. H. Hayes, mine superintendent of the Copper Queen Branch of the Phelps Dodge Corporation, has established at Bisbee a new mining division to be known as the Porphyry.

John E. Hardman, mining engineer and one of the founders of the Canadian Mining Review, died April 3d, aged 69 years.

Solon Shedd, head of the Department of Geology at the State College of Washington, State Geologist of Washington, will have charge of the John Casper Branner Memorial Geological Library, at Stanford University.

The West Virginia Geological Survey has just issued a detailed geological report on Mineral and Grant Counties, illustrated by 43 plates and 31 etchings. The report is accompanied by a separate case of topographic and geologic maps on a comparatively large scale. The price of the volume including maps is $3.25, and of the topographic maps 50 cts. for each county. The geological maps are priced at 75 cts. for each county. The Survey has also announced that it can supply a topographic map of Ohio, Brooke and Hancock Counties for 75 cts. on the scale of one mile per inch. Those wishing the report or the maps should address the Survey at P. O. Box 848, Morgantown, West Virginia.

The Geological Society of Tampico was organized in April at Tampico, Mexico. The following officers were elected: Walt. M. Small, president; Paul Weaver, vice-president; R. Liebensperger, secretary and treasurer; A. H. Noble, chairman of committee on publications; Paul Weaver, chairman of technical committee.

The Oklahoma Geological Survey announces the publication of the following bulletins and circulars, which on account of state law must be sold at the prices listed (postage extra):

Bull. 32. Geology of the Southern Ouachita Mountains of Oklahoma, by C. W. Honess	$1.00	$0.15
Bull. 33. Geology of Love County, Oklahoma, by Fred M. Bullard	$ .50	.05
Circ. 10. A Siluro-Devonian Oil Horizon of Oklahoma, by Geo. D. Morgan	.10	.02
Circ. 12. Stratigraphic Position of the Franks and the Seminole Conglomerates of Oklahoma, by Geo. D. Morgan	.25	.04